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RESEARCH ON MATERIALS FOR OFFSHORE STRUCTURES AND ARCTIC VESSELS - STEELS

Welding Institute of Canada Report RC307/1/89
"WELDMENT TOUGHNESS PROPERTIES FOR ARCTIC AND OFFSHORE WELDMENTS"
PHASE I
Sponsors: CLA, WIC Research Funds,
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EXECUTIVE SUMMARY

A primary consideration in the writing of standards for Arctic structures must be the avoidance of brittle fracture. The development of elastic-plastic fracture mechanics has enabled quantitative specification of toughness requirements based on design stresses and conceivable flaw sizes, but validation using structural-scale tests is needed to give credence to the calculations. Toward this objective, the federal Government, through the Interdepartmental Panel on Energy Research and Development (PERD), has supported the design and construction of a wide plate test facility at the Welding Institute of Canada. This facility is now fully operational and has been used in a previous program for Government and industry to characterize the HAZ toughness of potential steels for Canadian offshore applications. Several consumables available in Canada have been identified for Canadian offshore and Arctic applications. The objectives of the present investigation were to perform wide plate tests on SMAW metal deposited with E48018-1 electrodes produced by a Canadian manufacturer and to validate the prediction of structural performance from the small scale CTOD test results on the same weld metal.

Butt welds were prepared in a modified CSA G 40.21 Gr. 350 WT steel using CLA LA 18-Plus electrodes. Welding was performed in the vertical up position with single-V grooves for 25 mm thick plates and double-V grooves for 50 mm thick plates. The welds in 25 mm thick plates were used for CTOD tests and the welds in 50 mm thick plates were used for CTOD, tensile and wide plate tests. The experimental procedures and the results obtained are presented in this report. Further analysis and interpretation of the results will be carried out at MTL/CANMET.

RECHERCHE SUR LES MATÉRIAUX POUR LES STRUCTURES EN HAUTE MER ET LES ACIERS POUR LES NAVIRES ARCTIQUES
Institut de Soudage du Canada, Rapport RC307/1/89
"PROPRIÉTÉ DE RÉSILIENCE DES ASSEMBLAGES SOUDÉS POUR APPLICATIONS EN HAUTE MER ET EN RÉGIONS ARCTIQUES"
PHASE I
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RAPPORT EXÉCUTIF

Lors de la rédaction de normes concernant les structures destinées aux régions arctiques, une des premières préoccupations consiste à éviter les ruptures fragiles. La développement de la mécanique de rupture élastique-plastique a permis de spécifier des exigences quantitatives de résilience basées sur les contraintes de conception et les dimension acceptables de défauts. Cependant, la validation par des essais à échelle structurale est nécessaire pour donner une crédibilité à ces calculs. Dans ce but, le gouvernement fédéral, par l'intermédiaire du Comité Interdépartemental sur la Recherche et le Développement de l'Energie (PERD), a financé la conception et la fabrication d'un banc d'essai sur plaque large à l'Institut de Soudage du Canada. Cet équipement est maintenant opérationnel et a déjà été utilisé au cours d'un programme gouvernement-industrie. Ce programme consistait à caractériser la résilience de la ZTA d'aciers potentiels pour les applications canadiennes en haute mer et dans l'Arctique. Plusieurs produits d'apport disponibles au Canada ont été identifiés pour ces applications. Les objectifs de la présente recherche étaient de réaliser des essais sur plaque large de métal déposé par le procédé SMAW à l'aide d'électrodes E48018-1 produites par des manufacturiers canadiens. Ils consistaient également à valider les prédictions de tenue structurale obtenues par les résultats d'essai CTOD à petite échelle réalisées sur le même métal déposé.

Des soudures bout-à-bout ont été effectuées sur un acier ACNOR G40.21 Gr 350WT modifié avec des électrodes Air liquide LA 18 Plus. Les soudures ont été réalisées en position verticale montante sur une préparation en V simple pour les plaques de 25 mm et sur préparation en V double pour les plaques de 50 mm. Les soudures sur les plaques de 25 mm ont été utilisées pour les essais CTOD et les soudures sur les plaques de 50 mm ont été utilisés pour les essais CTOD, de traction et de plaque large. Les procédures expérimentales et les résultats obtenus sont présentés dans ce rapport. D'autres analyses et interprétations de ces résultats seront effectuées par MTL/CANMET.

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1.0 Introduction

Welded structures and marine vessels operating in the Canadian offshore and Arctic regions must have high reliability because of the high risks to life and environment associated with structural failure in harsh operating conditions. In recognition of this fact, industry and government have been cooperating in the development of standards for design and material selection for offshore structures and Arctic vessels.

A primary consideration in the writing of standards for Arctic structures must be the avoidance of brittle fracture. The development of elastic/plastic fracture mechanics (1, 2) has enabled quantitative specification of toughness requirements based on design stresses and conceivable flaw sizes for small scale tests. However, validation using structure-scale tests is needed to give credence to the calculations. Toward this objective, the federal government, through its Interdepartmental Panel on Energy Research and Development (PERD), has supported the design and construction of a wide plate test facility at the Welding Institute of Canada. This facility is now fully operational, and has been used in a program for government and industry to characterize the HAZ toughness of potential steels for Canadian offshore applications (3). The characterization of weld metal toughness still needs to be performed. MTL/CANMET have been evaluating the CTOD toughness of the weld metals deposited using SMAW, GMAW, FCAW and SAW processes for several years under the government research programs. Even though there are several consumables available in Canada which have the potential for Canadian offshore and Arctic applications, no wide plate tests have been performed for any of the weld metals deposited by these consumables to check the validity of CTOD toughness.

Generally, a wide plate test involves fatigue precracking of the massive test plate. However, the heavy duty machine needed is not available in Canada, so the crack tip of the wide plate defect is sharpened by a 0.15 mm thick saw blade. Small scale CTOD tests show that the sharpness of the crack tip has an effect in shifting the toughness transition temperature, i.e., as the sharpness increases transition temperature also increases. However, the effect of notch sharpness on wide plate fracture strains still needs to be investigated.

In view of the above, a 50:50 Government and Canadian Liquid Air sponsored project was initiated at the Welding Institute of Canada. The objectives of this investigation were the following:

a) To evaluate the CTOD toughness of shielded metal arc weld metal deposited with E48018-1 electrodes produced by a Canadian electrode manufacturer, using specimens containing a fatigue precrack and fine saw cut (0.15 mm thick) defect and compare the effect of crack type on the toughness.

b) To perform wide plate tests for the above weld metal and validate the prediction of structural performance from the results of small scale (CTOD) tests.

The experimental procedures used and the results obtained for the program are presented in this report. The analysis of the results will be carried out by Dr. W. Tyson at MTL/CANMET.

2.0 COD Design Curves

Recent developments in the COD design curve approach have yielded the following relationships between the CTOD value, tolerable defect parameter and/or effective applied strain in a wide plate test:

$$\frac{\delta}{2\pi e_y \bar{a}} = (e_c/e_y)^2 \text{ for } \frac{e_c}{e_y} \leq 0.5 \quad (1)$$

$$\frac{\delta}{2\pi e_y \bar{a}} = e_c/e_y - 0.25 \text{ for } \frac{e_c}{e_y} > 0.5 \quad (2)$$

where δ = CTOD value
$e_y = \sigma_y/E$, E = Young's modulus
σ_y = yield strength of the material
$\bar{a}$ = half through thickness crack length
e_t = effective or tolerable strain = σ_t/E
σ_t = the effective applied stress

By substituting CTOD test values into the above equations, it is possible to calculate (a) the maximum defect size for a known applied effective stress and/or (b) the tolerable strain for a given defect size of a structure or a wide plate. The above equations were used in the present investigation to determine the crack size and/or the tolerable strains for the wide plates from the CTOD values of the weld metals.

3.0 Experimental Procedures

3.1 Material

3.1.1 Steel

The base material used for the test welds was a modified CSA G40.21 Gr 350WT steel made to meet the requirements of Lloyd's LT60 specifications. This steel was produced specifically for low temperature offshore applications under the Government funded offshore development program. The steel used in this study was normalized and the composition and mechanical properties are given in the Mill reports (Appendix A) .

The 25 mm thick plate was used to prepare butt welds for CTOD tests to determine the notch effects on toughness and also to confirm the previous CTOD test results of MTL/CANMET. For previous test results (4) refer to CVN and CTOD data given for E48018-1 electrode weld metal in Figure B1 and Tables B1 and B2 (Appendix B). The 50 mm thick plate was used to prepare wide plate butt welds for wide plate tests as well as CTOD tests.

3.1.2 Consumable

The SMAW consumable CLA LA-18 Plus, 3.2 mm in diameter, conforming to AWS E 48018-1 specification was used to perform all the test butt welds. The butt welds in the 25 mm

thick plates were prepared at the Welding Institute of Canada using the same SMAW consumable supplied by CLA. All the butt welds in 50 mm thick plates were prepared at CLA.

3.1.3 Welding Procedure for 25 mm Thick Plate

For weld metal CTOD tests, six 150 mm wide x 600 mm long x 25 mm thick pieces of the steel were prepared for butt welding along the 600 mm length of the plate. A single-V joint with 60° groove, 0-3 mm land and 0-3 mm root gap was prepared by flame cutting and grinding. Three strong backs were fillet welded on the root side of the plate at 1/4, 1/2 and 3/4 length of the plate. The plate was held vertically by welding it to a table. The plate was preheated to 38°C. The welding was performed in the vertical up position using a stringer bead technique with freshly opened LA-18 Plus electrodes. When side one was completely welded, the root was backgouged, ground to sound metal and side two was welded. The welding parameters and bead sequencing used are given in the welding data sheet - 1 (Appendix A).

3.1.4 Welding Procedure for 50 mm Thick Plates

Twelve 1000 mm long x 500 mm wide x 50 mm thick steel plates were butt welded along the 1000 mm length to obtain 6 welds for weld metal wide plate tests as well as CTOD tests. A double-V groove joint (2/3, 1/3) with a 60° groove x 0-3mm land x 0-3mm root gap was prepared. Three strong backs were used on side one perpendicular to the length, two at locations 150 mm in from the end and one at the centre of the plate. The welding was done in the vertical up direction using a 38°C preheat. For side two, the root was backgouged and ground to sound metal and then welded. The welding parameters, interpass temperatures and bead sequencing are shown in the welding data sheets-2 to 7 (Appendix A).

One test weld was used for CTOD and tensile tests and five for wide plate tests. Weld lengths were parallel to the rolling direction and the plates. All the welds after removing the strong backs had a maximum distortion, at the centre of the plate perpendicular to the weld

length, of 2-3°. However, the distortion measured perpendicular to the weld approached zero at the ends of the weld. There was some distortion along the length of the weld, which could not be easily measured due to weld metal reinforcement over the plate.

3.1.5 Tensile Tests

Five tensile specimens 12.7 mm in diameter x 50 mm in gauge length were prepared from the weld metal with tensile axis both parallel to the weld length and transverse to the weld length (cross weld). Also two base metal tensile specimens were prepared with tensile axis parallel to the rolling direction. The specimens were machined for each type from t/4 locations of the plate and/or the weld. For each type two tensile tests were carried out at -50°C using the cooling chamber set up shown in Figure 1. Tensile test for the weld metal was also carried out at room temperature using one specimen with tensile axis parallel to the weld axis.

3.1.6 CTOD Tests

Preferred CTOD specimens (5) were machined for the weld metals in 25 and 50 mm thick plates. Twenty-three 25 x 50 mm and five 50 x 100 mm full thickness CTOD specimens were prepared. Ten of the 25 x 50 mm CTOD specimens were fatigue precracked and tested at -50° $\pm$ 2°C. Prior to fatigue precracking, the notch ligament was locally compressed from both sides to give a plastic indentation depth equal to 0.25% of the thickness on each side. For the rest of the 25 x 50 mm CTOD specimens, the crack tip was sharpened by saw cutting with a 0.15 mm thick saw blade instead of fatigue precracking. Ten of these saw cut cracked specimens were tested at -50° $\pm$ 2°C and the remaining three were tested at -30° $\pm$ 2°C.

All the 50 x 100 mm CTOD specimens were saw cut with 0.15 mm thick blade to sharpen the crack tip and tested at -50° $\pm$ 2°C. The CTOD tests were carried out as per BS 5762 (5). After the test, all the fracture surfaces were sprayed with WD-40* fluid to prevent rusting.

(* WD-40 Products Ltd., Etobicoke, Ontario)

3.1.7 Wide Plate Tests

3.1.7.1 Loading End Attachment

Five 1 m long x 1 m wide x 50 mm thick plate butt welds were prepared for weld metal wide plate tests with through thickness defects. Initially, each wide plate was attached to loading end attachments. This was done in a special alignment jig which consisted of a platform with horizontal and vertical I beams (Figure 2).

The loading end attachment consists of a 140 mm thick steel plate (Figures 2, 3, and 10). Two steel lugs are welded symmetrically on each side of the plate. The loading surface of each lug is perpendicular to the plate surface. Each lug has a hole where the centre rod from the loading capsule of the wide plate test rig is inserted for the test. The loading lugs are positioned and machined to exactly line up with and fit the loading capsules of the wide plate test rig (Figure 10). The plates of the two end attachments are placed vertically on the horizontal I-beam and the free ends (ends that are not going to be welded to the wide plate) of the attachments are pushed against the vertical I-beams and the lugs are strapped loosely against these I-beams. The ends of the plates of the attachments to be welded to the wide plate, are reduced in thickness to match the thickness of the wide plate which rests on rollers whose heights can be adjusted using four vertical bolts attached to the rollers. The bottom lugs are supported by hydraulic jacks. The loading surfaces are adjusted to the vertical by using the jacks and the support rollers. This is checked by a spirit level and plumb line. The bottom horizontal I-beam can be moved along the length of the platform and fastened by bolts. Fine movement, horizontal or angular, of the horizontal I beams can be made using two horizontal bolts.

At first, the loading ends were aligned. The plate surfaces and the loading surfaces of the lugs were adjusted to the vertical using the roller support, the jacks and the horizontal movement of the I-beams. After checking the verticality with the spirit level, the alignments of the loading end plates were accomplished by keeping the distance between the holes of the lugs corresponding to the same loading capsule to be 2260 mm (89"). Also, the alignment

of the plates was checked by measuring the diagonal distance between the holes of the top four and bottom four lugs. After alignment, the loading ends were strapped and secured tightly against the vertical I-beams to prevent movements that might be caused by welding.

The wide plate was placed vertically in between the loading ends such that the test weld was vertical. Due to distortion in the test plate, only ends of the plate were aligned with joining ends of the loading end attachments (Figure 3). The plate was joined to the loading ends by consumable guide electroslag butt welding. Standard welding parameters with Hobart PS 588 - Linde 124 wire - flux combinations were used for electroslag welding (Figure 4). Once the plate was welded the width of the test plate (length of the test weld) was symmetrically cut to 940 mm.

3.1.7.2 Through Thickness Defect and Instrumentation

A 100 mm through thickness defect was saw cut, for the first test, using a power saw from an initial centrally drilled hole. The final 4-6 mm at the defect tip were cut using a 0.15 mm thick saw blade (Figure 5). For the first test, a notch length was calculated from the minimum CTOD value at -30° C. For the remaining four tests, carried out at -50°C, the defect sizes were 200 mm for three and 100 mm for one.

In order to determine whether the residual stresses were relieved while drilling and cutting the defect, for the fifth plate, 3mm strain gauges were attached at the locations along the defect line (weld axis) as shown in Figures 6 and E1 (Appendix E). Ten gauges were put close to one of the defect tip on one side and other ten were put close to the other defect tip on the other side. The strain gauges were closely spaced such a way that five would fall below the final defect tip and five above. Five were put below the location of final defect tip so that each of these gauges could be cut and strain in the adjacent gauge in tact could be recorded. Also, two strain gauges were put along the central axis parallel to the loading axis one on each side of the plate and the central defect hole (Figure 6 and E1). After attaching and zeroing the strain gauges, the drilling and saw cutting of the defect was performed. Strain changes in the gauges were recorded at specific points as the defect was cut. The strain

cut. The strain readings recorded would give some indication of how the residual stress present in the plate might have released while putting in the defect.

Quarter inch (12.5mm) strain gauges were put along the central tensile axis as well as along the defect axis of the weld on both sides of the plate. Along the length of the weld where strain gauges were put about 25 mm of the weld was ground flush with the surface of the plate. Also, at the defect location the weld reinforcement was ground flush with the plate surface, approximately 50 mm longer than the defect length, on both sides of the plate. Thermocouples were attached to the surface of the plate and to the cooling attachment of the plate. The strain gauge and thermocouple locations are shown schematically in Figures 8 and 9. Figure 5 shows the wide plate with the defect and the instrumentation.

The strain gauges and thermocouples were connected to the data acquisition system and/or the manual monitoring systems. A clip gauge was attached through knife edges at the tip of the defect on one side within the defect (Figure 7). The clip gauge reading was monitored during the test by a data acquisition system and a strip chart recorder.

3.1.7.3 Cooling and Wide Plate Testing

A 500 mm wide styrofoam cooling box (chamber) was attached to the test weld location of the wide plate. The wide plate was placed in the wide plate test rig shown in Figure 10 and the loading lugs were aligned with the loading capsules as shown schematically in Figures 11 and 12. The strain gauge, thermocouple, clip gauge and LVDT connections were made for recording the data. The features of the wide plate test rig are given in Table I. The hydraulic system shown in Figure 13 which is operated pneumatically by high pressure nitrogen gas, is connected to the loading capsules. The pressure in the system was calibrated against a precalibrated dial gauge and voltmeter. The applied pressure was monitored continuously by means of a strip chart recorder. Once the pressure was calibrated, the cooling chamber was connected to the liquid nitrogen vapour circulation system. The liquid nitrogen was passed through a centrifugal pump circulation system which blows and circulates the cold vapours from liquid nitrogen into the cold box thus cooling the test section. Complete wide

plate test assembly is shown in Figure 14. The temperature of the test section was monitored continuously and controlled manually within ±5°C of the test temperature. The test section was cooled to the test temperature of -30°C or -50°C. The thermocouple readings for each wide plate test recorded are given in Tables C1 to C5 (Appendix C).

When the test section reached the test temperature as indicated by the thermocouples, the strain gauges, LVDT and the pressure in the line were zeroed. The test weld was then loaded manually in steps of 500 or 1000 psi pressure increments. At each pressure increment the strain gauge, LVDT, clip gauge and temperature readings were recorded. The test was continued till fracture of the weld (plate) occurred. Only the first test was stopped prior to fracture when yielding of the base plate occurred. Later tests were continued to fracture even though yielding was observed in some of the strain gauge readings for tests 3, 4 and 5. In test 2, the fracture was completely brittle (Figures 15 and 16). The tests 3, 4 and 5 (Figures 17 and 18) also failed in a brittle fashion with an initial ductile tear in the weld metal (Table II). As soon as the plate fractured, the pressure and clip gauge readings at the verge of fracture were written down from the strip chart recorder. The cold box was removed from the plate and the fracture surfaces were sprayed with WD-40 fluid to prevent rusting. The fracture surfaces were removed from the wide plate by cutting the plate ≃ 25mm away from the fracture surface parallel to the weld length. The average defect length 2a was measured for each wide plate (Table II).

3.1.8 Metallography and Fractography

Each wide plate and CTOD weld section was polished, etched and macrographs were obtained (Procedure sheets-1 to 7 in Appendix A). Also, some of the CTOD and wide plate test fracture surfaces were photographed (Figures 18-20).

Fracture surfaces from some of the CTOD test and wide plate test pieces were subjected to fractography and quantitative metallography. Initially, the fracture initiation site was identified as the point of convergence from the chevron marks on the fracture surface using a binocular stereo viewer. To locate the exact location of the initiation site a SEM was used. However,

this exercise was not completed due to constraints on resources allocated to this program.

A limited amount of quantitative metallography was performed to determine the area fractions of different microstructures including columnar, reheated coarse grain and fine grain regions present along the defect tip. This was done by sectioning perpendicular to the defect plane along the defect tip as per API Recommended Practice RP2Z. The microstructures of the approximate initiation sites were identified.

4.0 Results

4.1 Tensile Test Data

The yield strength, UTS and % elongation obtained for the weld metal, the cross weld and the base plate are given in Table III. The tensile test data for the weld metal are given in Tables D1, D2 and D7 (Appendix D). Also, the stress-strain curves are given in Figures D1 to D6 (Appendix D). Results show that the weld metal used overmatches the yield and tensile strengths of the base plate. The average lower yield strengths for the weld metal and the base material, at -50°C are 529 and 404 MPa respectively.

4.2 CTOD Test Data

The CTOD values obtained for specimens with saw cut defects are given in Table IV. Table V gives the CTOD values for the CTOD specimens with fatigue precrack. Some of the specimens showed bowl shaped and cusped fatigue precrack front, due to the presence of residual stresses, even after the notch ligament was locally compressed. The crack length measurements viz. a_{max}, a_{min} and a_{avg} showed that the CTOD values obtained from these specimens were still valid. On an average, 25 x 50 mm CTOD specimens with saw cut defects yielded higher CTOD values than the fatigue precracked defects. The CTOD test data for saw cut and precracked specimens are given in Tables D3 to D6 (Appendix D).

The CTOD values for 50 x 100 mm specimens are higher than those for the corresponding

25 x 50 mm specimens. This is contrary to the general finding that the thicker specimens yield lower CTOD values.

4.3 Strain Gauge Readings During Saw Cutting Defect

The changes in strain gauge readings during saw cutting of the defect in wide plate #5 were recorded. These stain gauge readings are given in Table E8 (Appendix E). The changes in readings show some kind of development taking place in the residual stress patterns of the wide plate during the drilling and the cutting of the defect. The microstrains as high as -1014 and 1067 (Table E8 in Appendix E) were observed after drilling the central hole and saw cutting the top half of the defect (west side in Figure E1 of Appendix E) respectively.

4.4 Strain Gauge Readings for the Wide Plate Tests

The strain gauge readings recorded at each jack pressure level during the course of the wide plate tests are given in Tables E1 to E6 (Appendix E). For each test, the strain readings measured along the tensile axis and along the weld length are plotted against the jack pressure in Figures 21 to 25. Each test showed that, at any jack pressure level, the strains recorded on one side of the plate were greater than the other side. This can be attributed to the distortion in the wide plate giving rise to uneven distribution of the loads resulting in bending.

4.5 Crack Tip Opening Displacement Values

Crack tip opening displacement (CTOD) values measured for the wide plate tests are given in Table E7 (Appendix E). The CTOD values were also plotted against the jack pressure for each wide plate test. The plots are shown in Figure 26.

4.6 Fractography and Metallography of Defect Tip

The results of the quantitative metallography, i.e., the weld metal microstructures sampled by the defect tips in CTOD as well as wide plate test specimens are given in Figures 27 and 28.

The area fractions of each weld metal microstructure sampled by the defect tips are given in Table VI. The reproducibility in sampling the microstructure by the defect tip seems to be reasonably good.

5.0 Acknowledgement

This project has been a 50:50 cost shared program with the Department of Supply and Services - MTL/CANMET. Support in kind has also been obtained from the Canadian Liquid Air who prepared all the wide plate welds required for the tests. Timely advice from Dr. W. Tyson and Prof. U. Mohaupt is also appreciated. Thanks are also due to Mrs. Catherine Neal and Mrs. Kathy Smith for putting this report together.

6.0 References

1. British Standards Institution, PD 6493 (1980).

2. Pisarski, H.G., "The CTOD Approach to the Specification of Fracture Resistant Welded Steel Structures for Arctic Service" in "Fracture Toughness Evaluation of Steels for Arctic marine Use", Ed. R. J. Thomson and C. Champion, CANMET/EMR, Ottawa, Oct. 1983.

3. Bala, S. R. and Santyr, S., "Evaluation of Heat Affected Zone and Weld metal Toughness in Selected Steels - Phase I", AMCA International Ltd., Report No. 7-184-071-099/F, Aug. 1986.

4. Braid, J. E. M., and Gianetto, J. A., "The Effect of PWHT on the Toughness of Shielded Metal Arc Weld Metals for use in Canadian Offshore Structure Fabrication", Aug., 1985, CANMET/PMRL Report: PMRL 85-44(OP-J).

5. British Standards Institution, BS 5762 (1979).

Table I

Features of Wide Plate Test Rig

- Loading in uniaxial tension
  4 x 1000 metric ton capsules
  75 mm stroke
  End frames designed to have sufficient stiffness to ensure even distribution of load

- Specimens: 1220 mm in width
  1220 - 1830 mm in length
  75 mm thick at maximum capacity of 4000 metric tons.

- Instrumentation: Strain gauges
  Thermocouples
  Clip Gauge etc.

- Pneumatically driven pump to provide 30,000 psi capsule pressure, controlled through the valves, load transfer through 254mm diameter jack from each capsule.

- Plates can be locally cooled

- Data acquisition system

Table II

Defect Size of the Wide Plates

Wide Plate	Test Temperature °C	Defect Length $2\bar{a}$ (mm)	Failure Pressure psi	Failure Micro-Strain*	Failure Mode
1	-30	100.0	13,300x	1958	No fracture
2	-50	203.0	9,857	956	Brittle
3	-50	96.4	14,400	2,280	Ductile tear-brittle
4	-50	200.0	16,200	1,257	Ductile tear-brittle
5	-50	198.0	14,500	1,164	Ductile tear-brittle

* Average of gauges E3, E8, W3 and W8.
x Test was stopped when yielding occurred.

Table III

Tensile Properties at -50°C

Properties	Parent Plate		Weldmetal			Cross-Weld	
	1	2	1	2	3*	1	2
G.L. (mm)	50	50	50	50	40	50	50
Diameter (mm)	12.7	12.7	12.7	12.7	10	12.7	12.7
Y.S. (MPa)							
Upper	452	561	556	567			
Lower	394	413	526	532			
0.2%					535	445	485
0.5%						488	517
T.S. (MPa)	555	565	619	634	612	596	600
Elong. (%)	40	40	29	30	28.5	26.5	25.5

* At room temperature (20°C)

Table IV

CTOD Data for Weld Metal From Saw Cut Defect

Specimen No.	Test Temperature °C	Specimen Size mm	CTOD values mm
1	-50	25 x 50	0.137 (u)
2	-50	25 x 50	0.221 (u)
3	-50	25 x 50	0.122 (u)
4	-50	25 x 50	0.223 (u)
5	-50	25 x 50	0.228 (u)
6	-50	25 x 50	0.315 (u)
7	-50	25 x 50	0.368 (u)
8	-50	25 x 50	0.135 (u)
9	-50	25 x 50	0.302 (u)
10	-50	25 x 50	0.160 (u)
1	-30	25 x 50	>0.780 (*)
2	-30	25 x 50	0.239 (u)
3	-30	25 x 50	>0.739 (*)
1	-50	50 x 100	0.213 (u)
2	-50	50 x 100	0.236 (u)
3	-50	50 x 100	0.140 (c)
4	-50	50 x 100	0.391 (u)
5	-50	50 x 100	0.572 (u)

Note: (u) - δ_u value

(c) - δ_c value

(*) - test was terminated since displacement exceeded the clip gauge range (3.75 mm) while load was still rising.

Table V

CTOD Values at -50°C for the Weld Metal Obtained
From 25 x 50 mm Specimens with Fatigue Precracked Defect

Specimen No.	CTOD Values
1	0.130 (u)
2	0.198 (u)
3	0.069 (u)
4	0.064 (c)
5	0.109 (u)
6	0.076 (u)
7	0.091 (u)
8	0.041 (c)
9	0.100 (u)
10	0.250 (u)

Note: (u) - δ_u value
(c) - δ_c value

Table VI

Quantitative Metallography

The Microstructures Sampled by the Defect Tips

Sp. Type	Size	Defect	Sp. No.	WM Microstructure, %		
				Columnar	CG	FG
CTOD	25 x 50	Saw cut	8	20.0	24.0	56.0
	25 x 50	Saw cut	9	14.0	31.0	55.0
	25 x 50	Fatigue	6	31.0	25.0	44.0
	25 x 50	Fatigue	10	13.0	25.0	62.0
	50 x 100	Saw cut	3	23.5	19.2	57.3
	50 x 100	Saw cut	4	28.0	23.0	49.0
Wide plate	50 x 940	Saw cut	#2	27.5	34.3	38.2

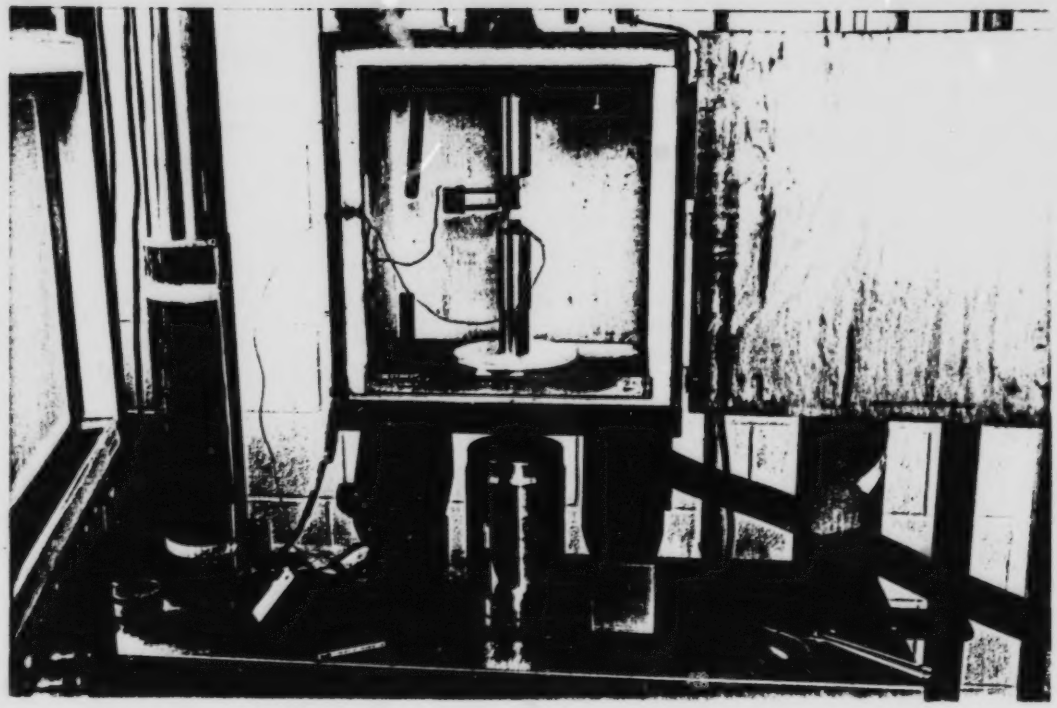


Figure 1. Set up for performing tensile tests at -50°C.

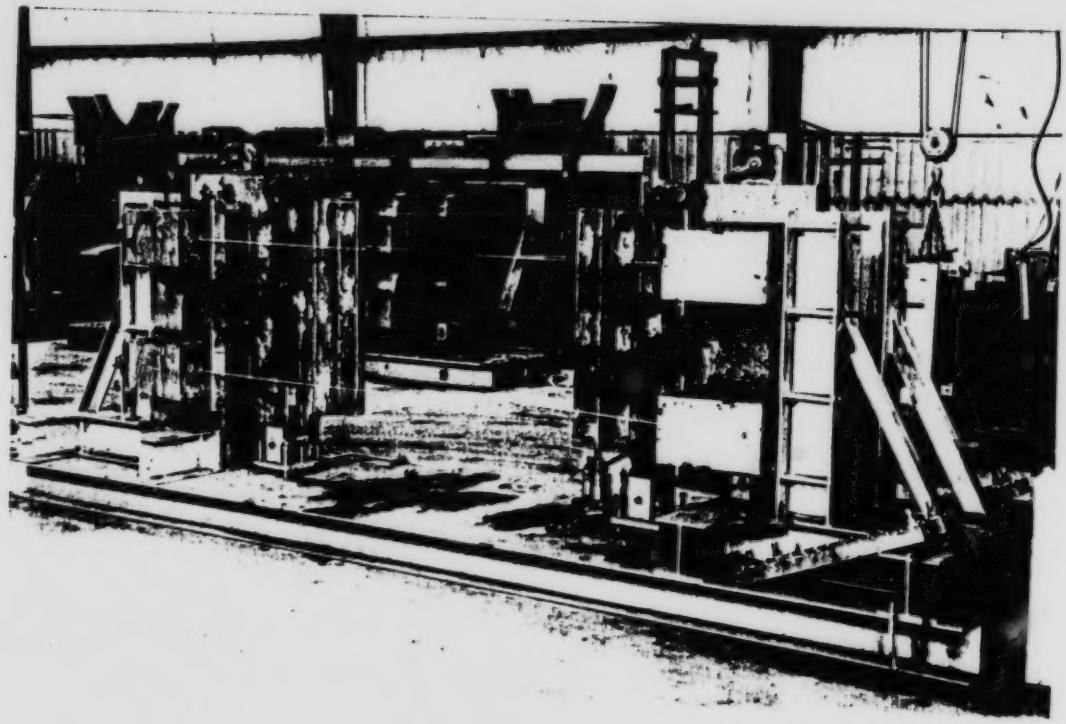


Figure 2. Alignment of loading end attachments in the alignment jig.

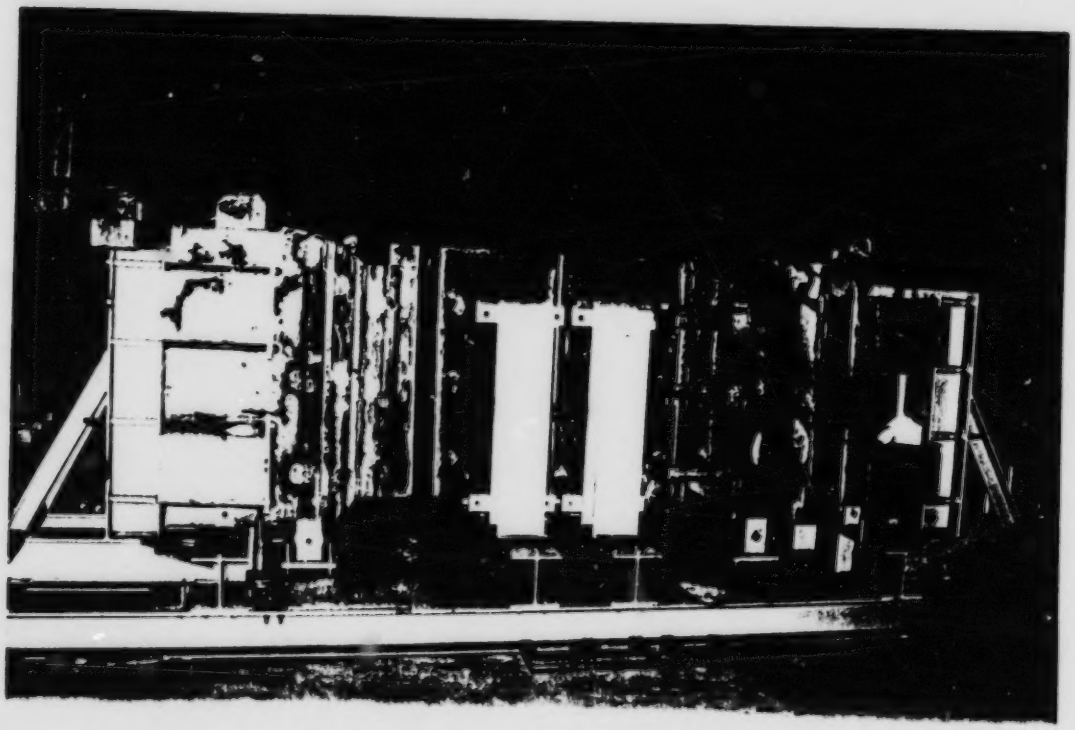


Figure 3. Wide plate alignment with the loading end attachments.

Figure 4. Electroslag welding of the loading end attachments to the wide plate.

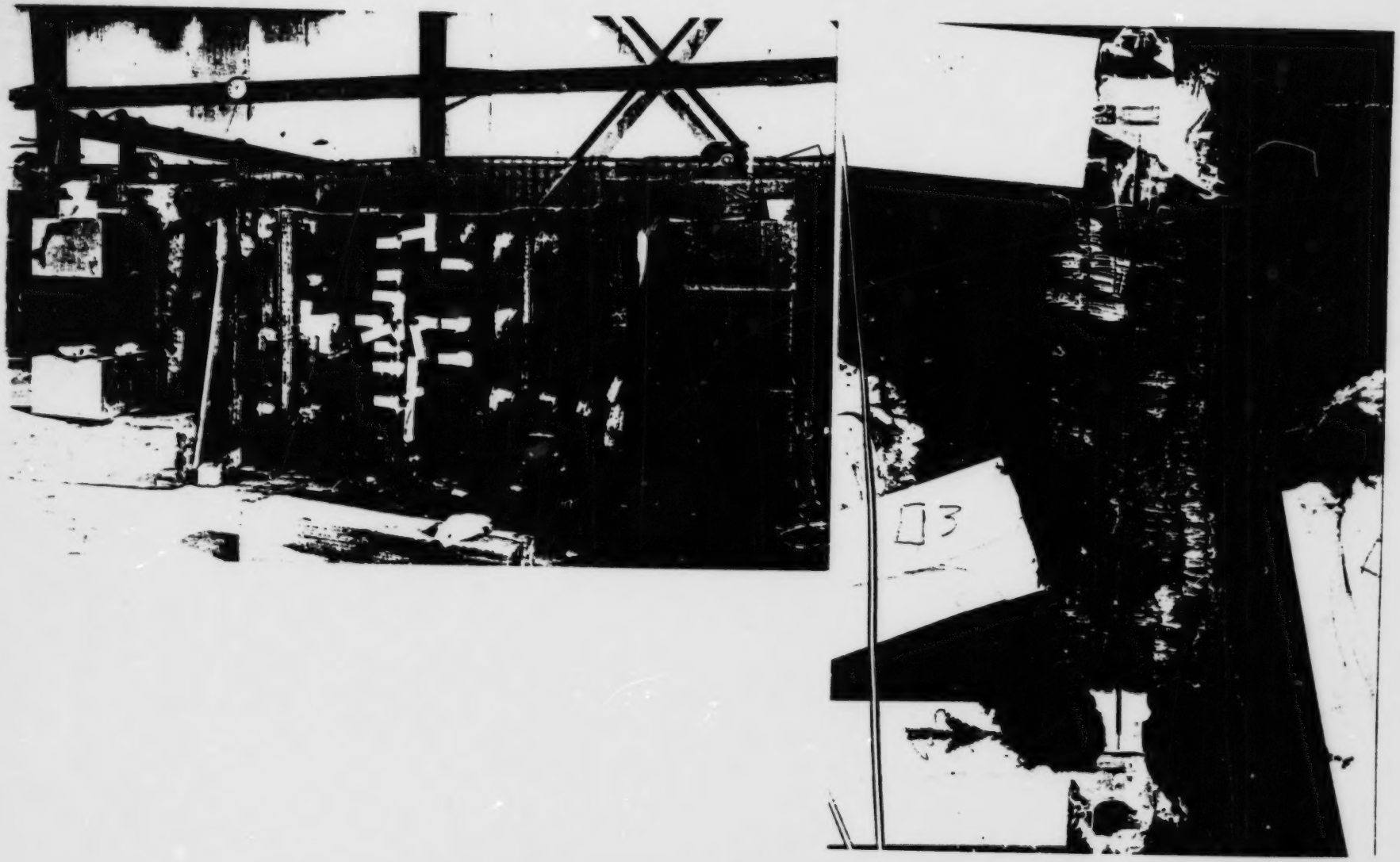


Figure 5. Through thickness defect in the weld metal of the wide plate. Arrows indicate the knife edge location for the clip gauge.

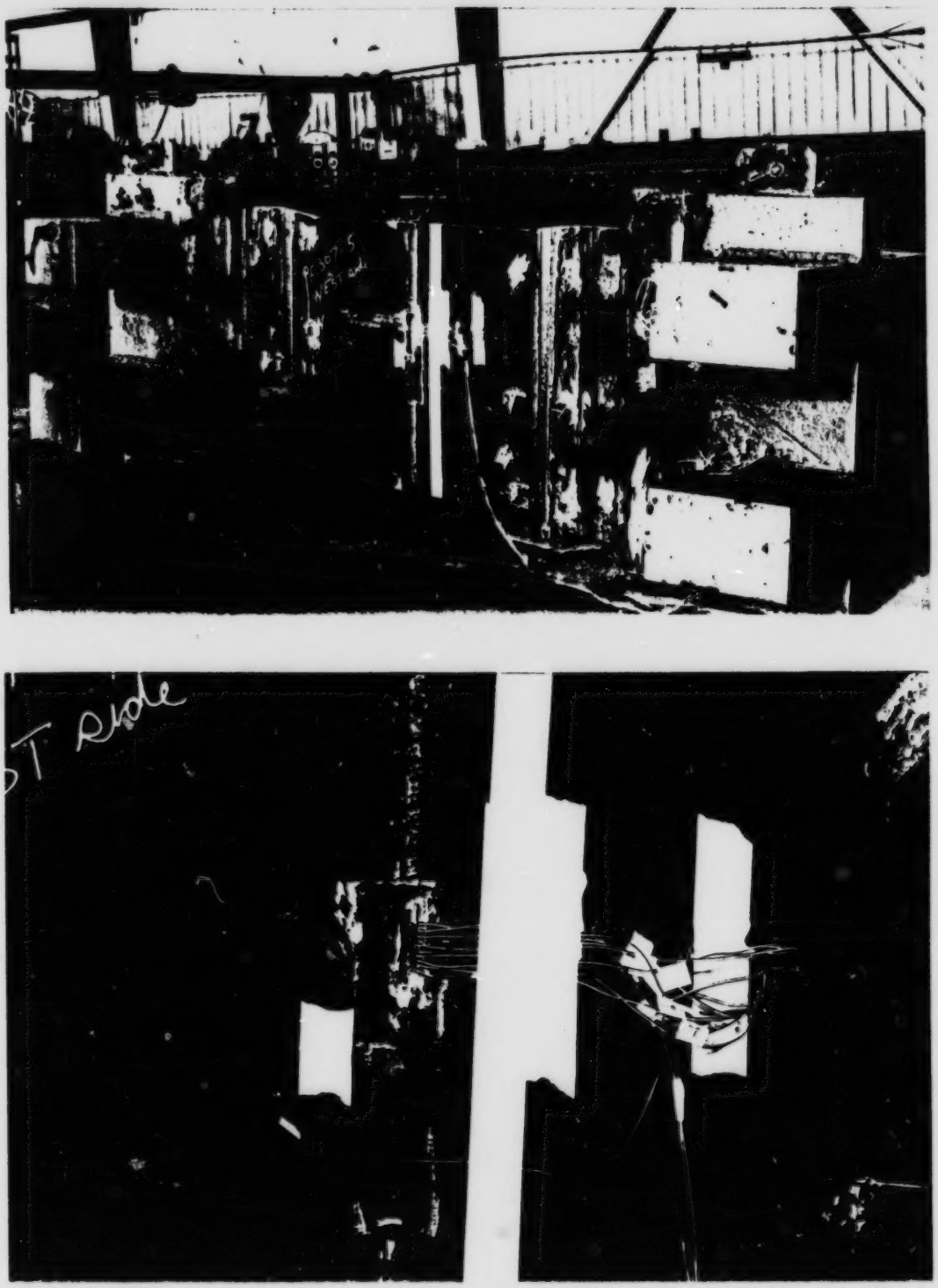


Figure 6. Wide plate showing the strain gauge locations for measuring the strain changes during cutting of the defect.

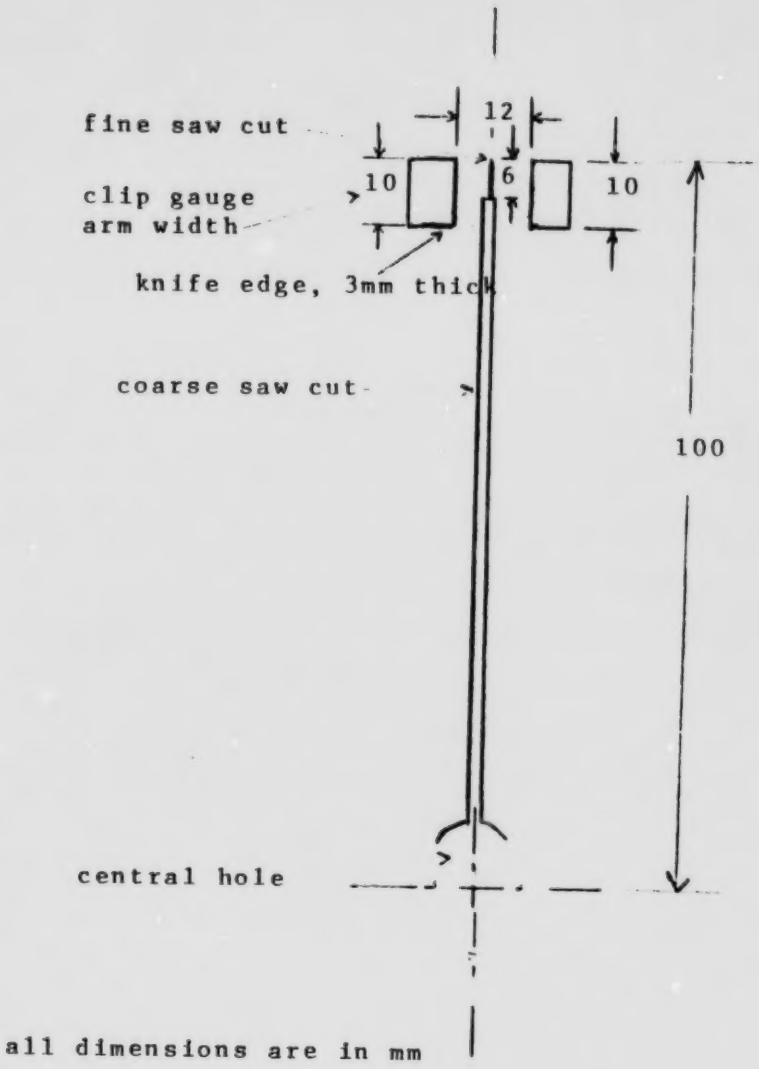


Figure 7. Knife edge location with repect to the defect tip of a wide plate.

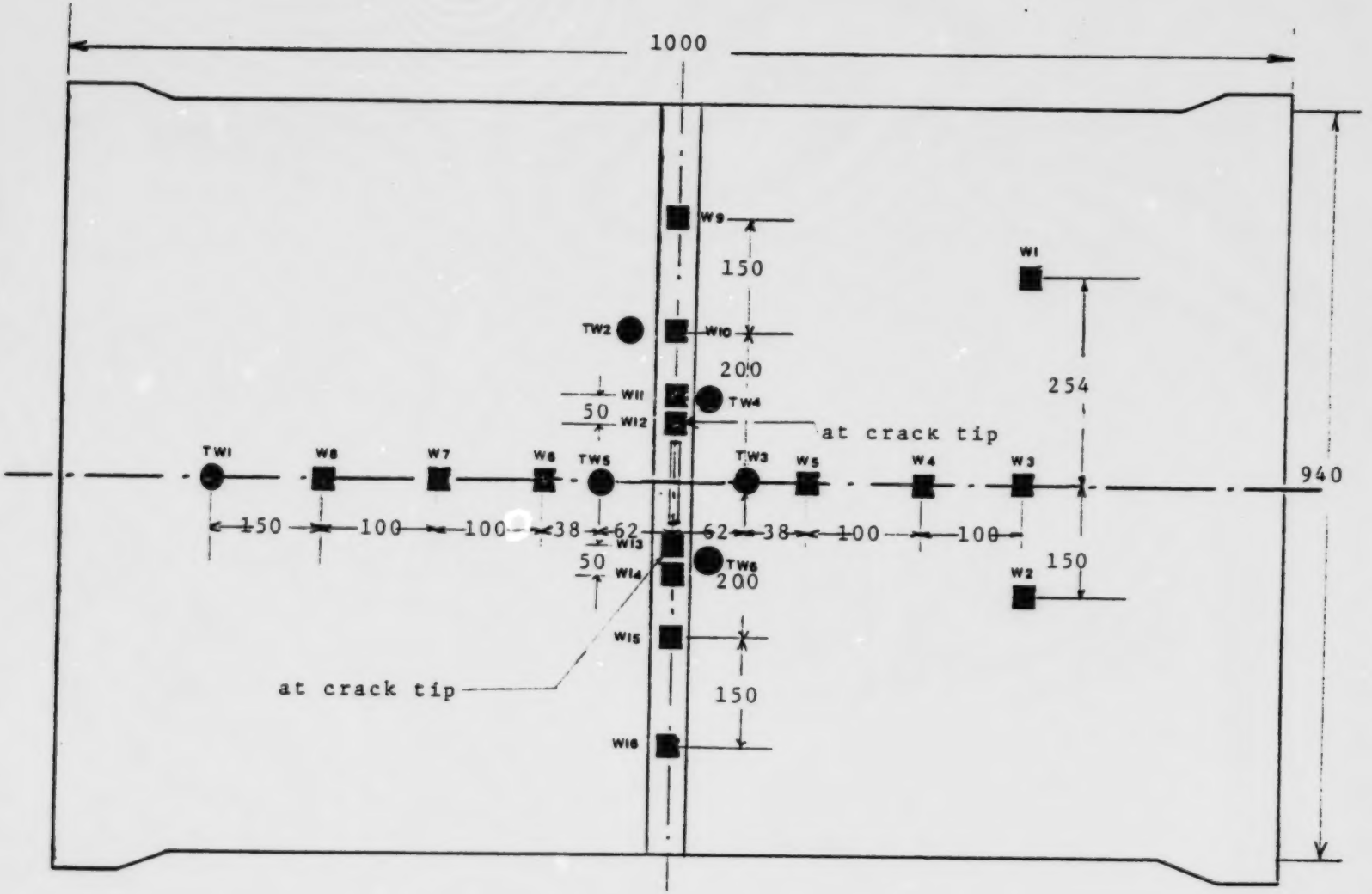


Figure 8. Schematic diagram showing the strain gauge and thermocouple locations of the wide plate on one side (west side of the plate).

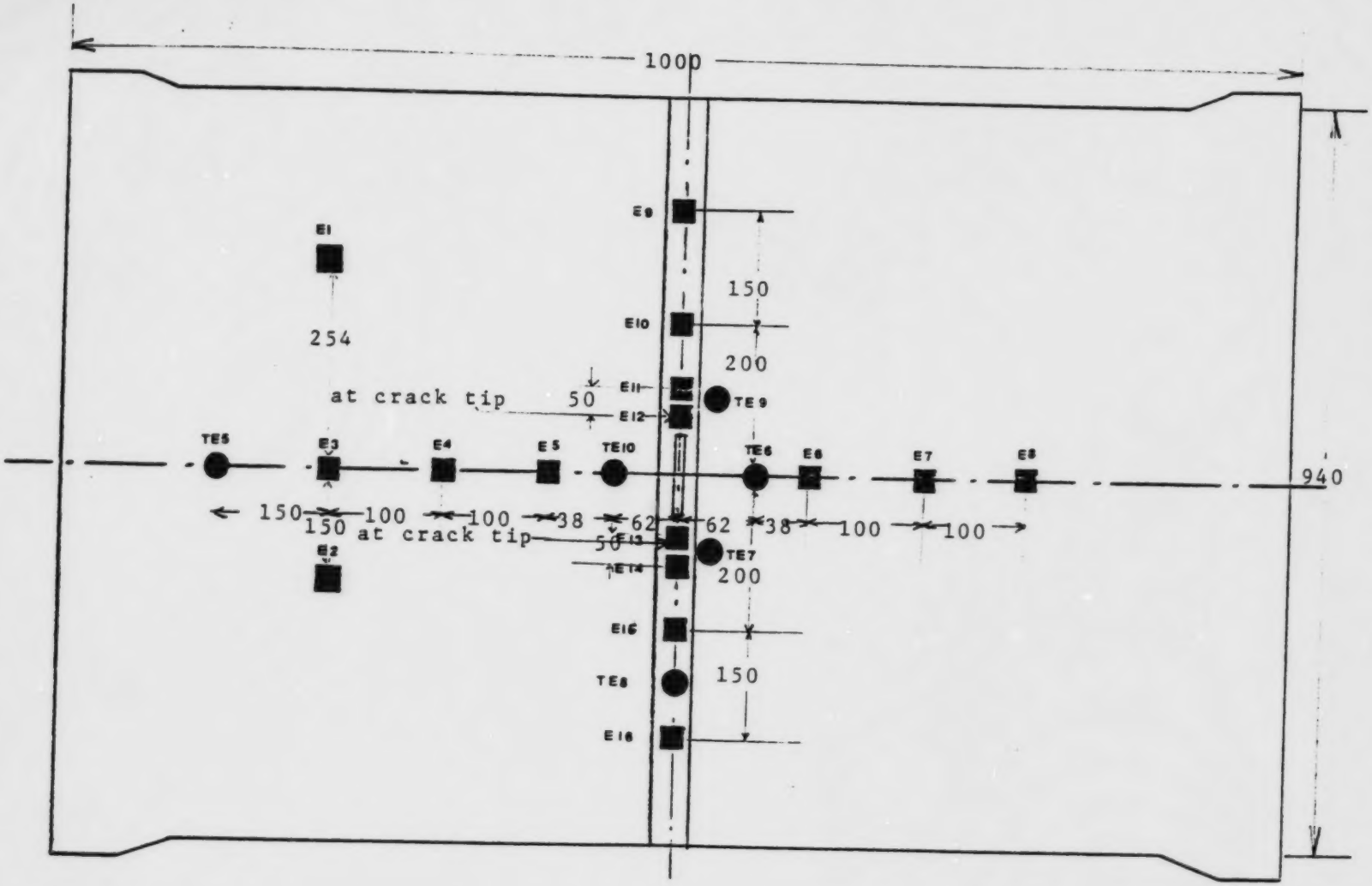


Figure 9. Schematic diagram showing the strain gauge and thermocouple locations of the wide plate on the second side (east side of the plate).

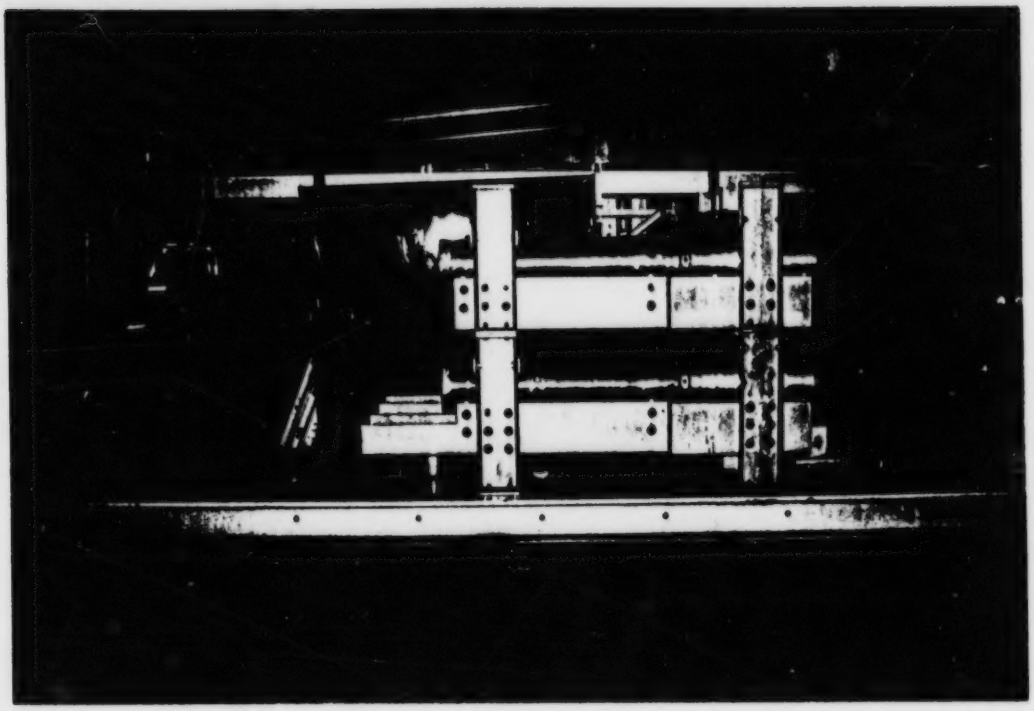


Figure 10. Wide plate test rig showing the loading capsules.

Figure 11. Diagram showing the wide plate specimen, the loading capsules and the lugs of the loading end attachments.

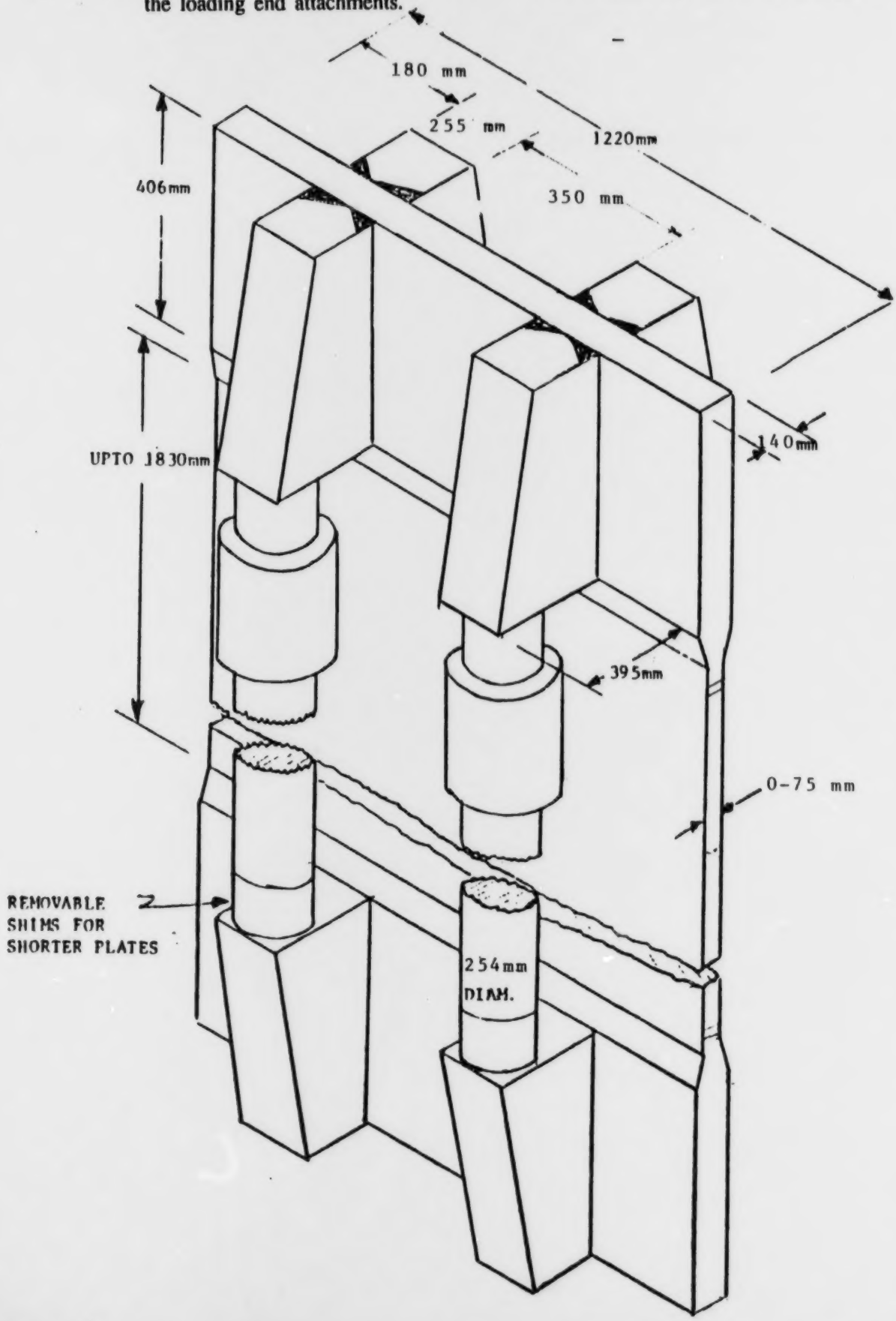
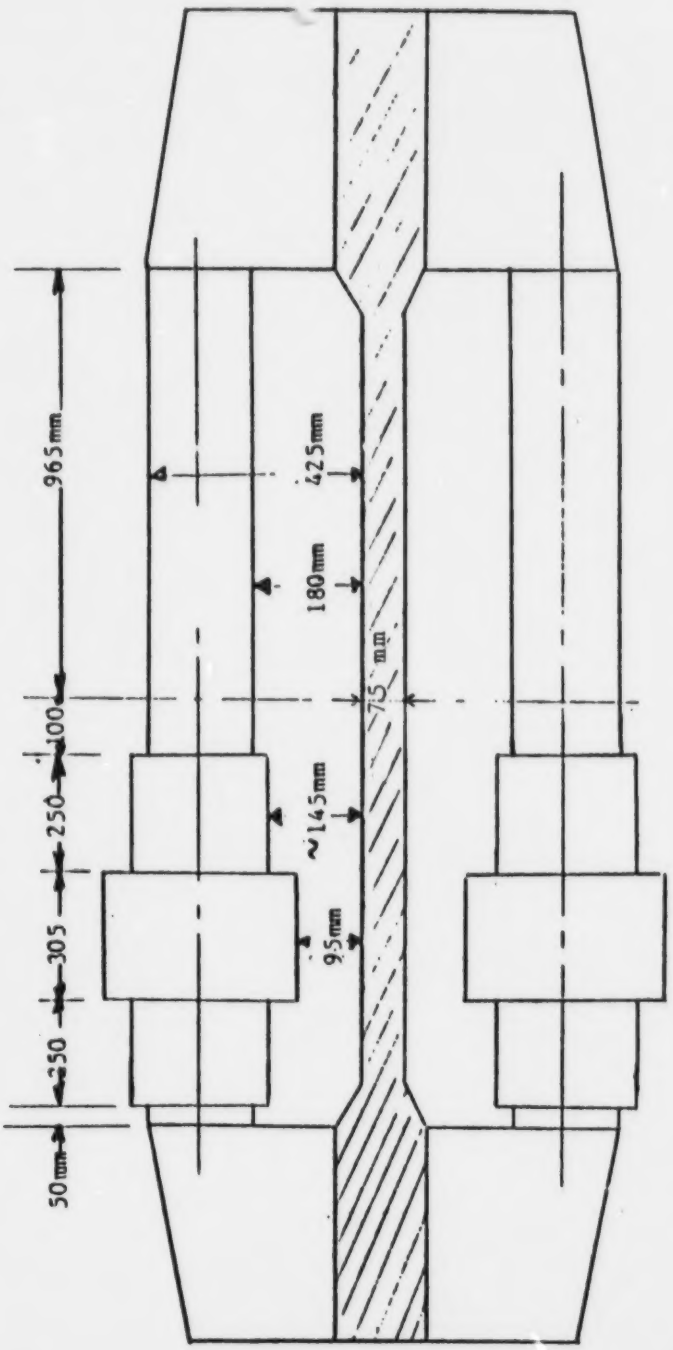


Figure 12. Wide plate specimen and clearance for 75 mm thick plate.



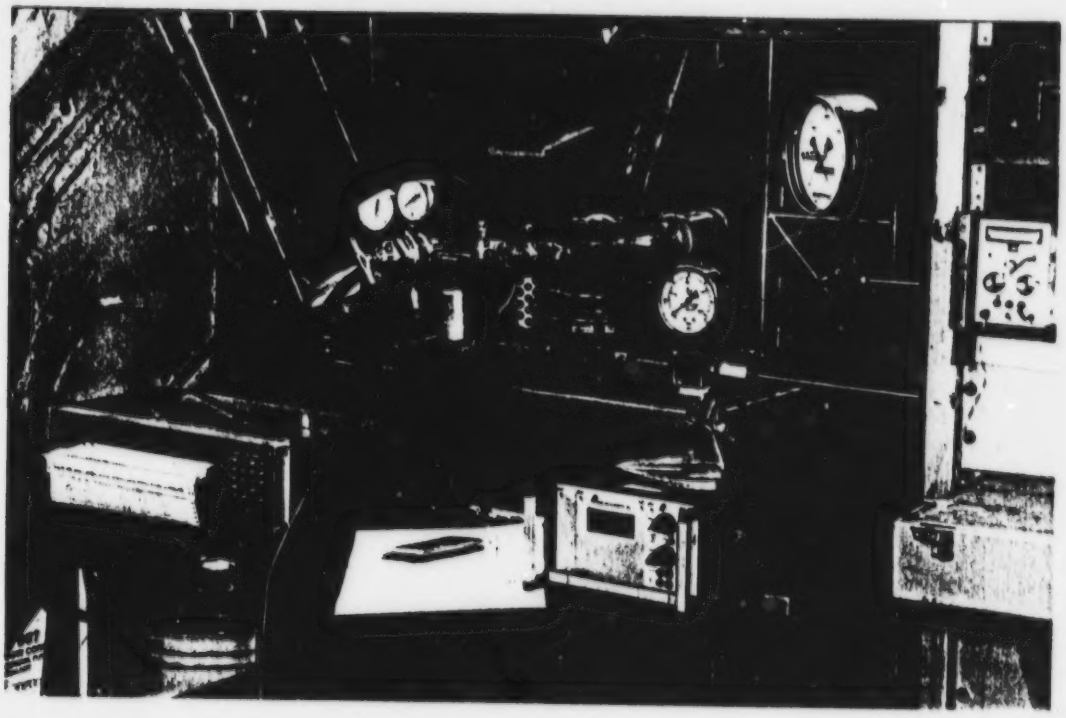


Figure 13. Hydraulic control system for loading the wide plate.

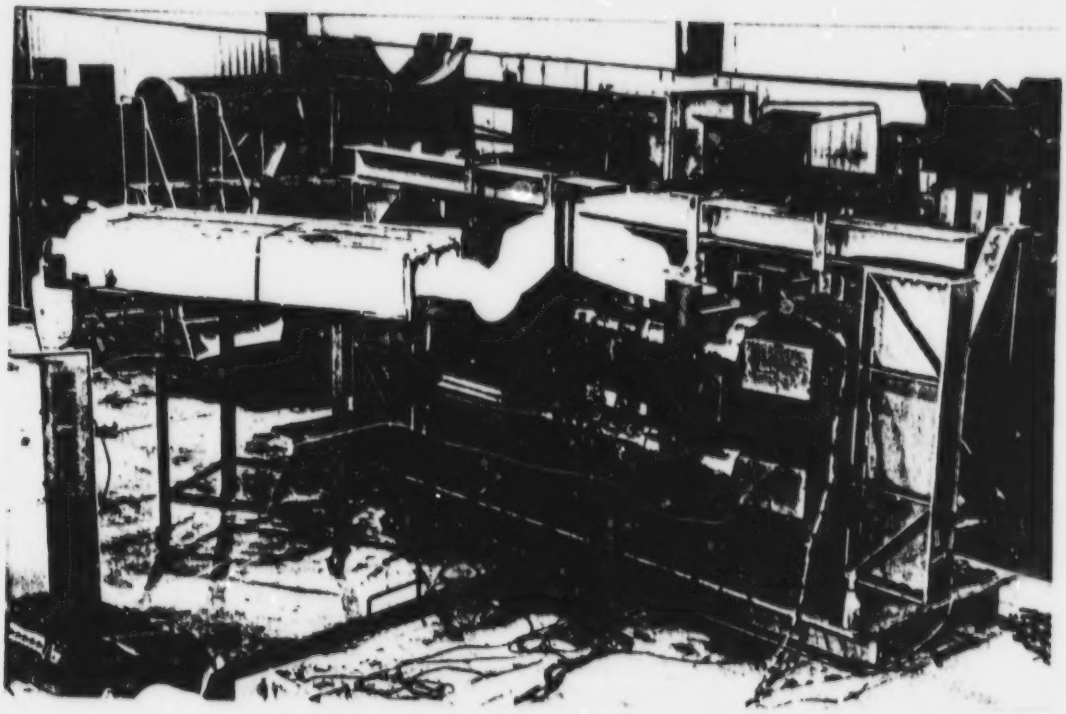


Figure 14. Wide plate test setup and the cooling system for the test section.

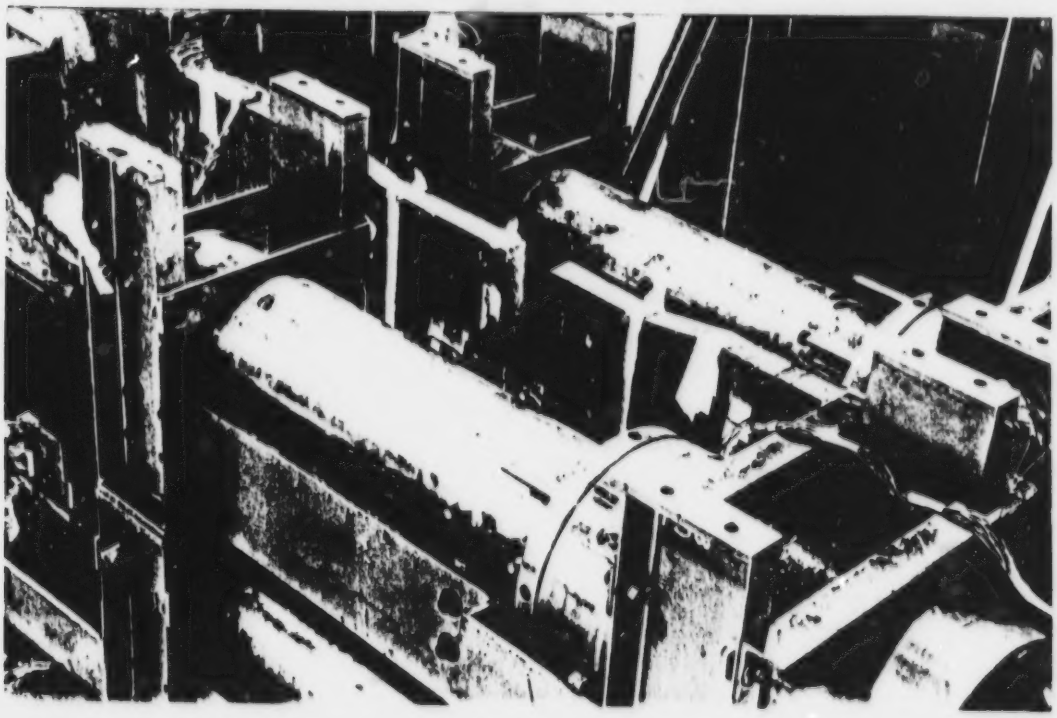


Figure 15. Fracture of the wide plate at -50°C in test #2.

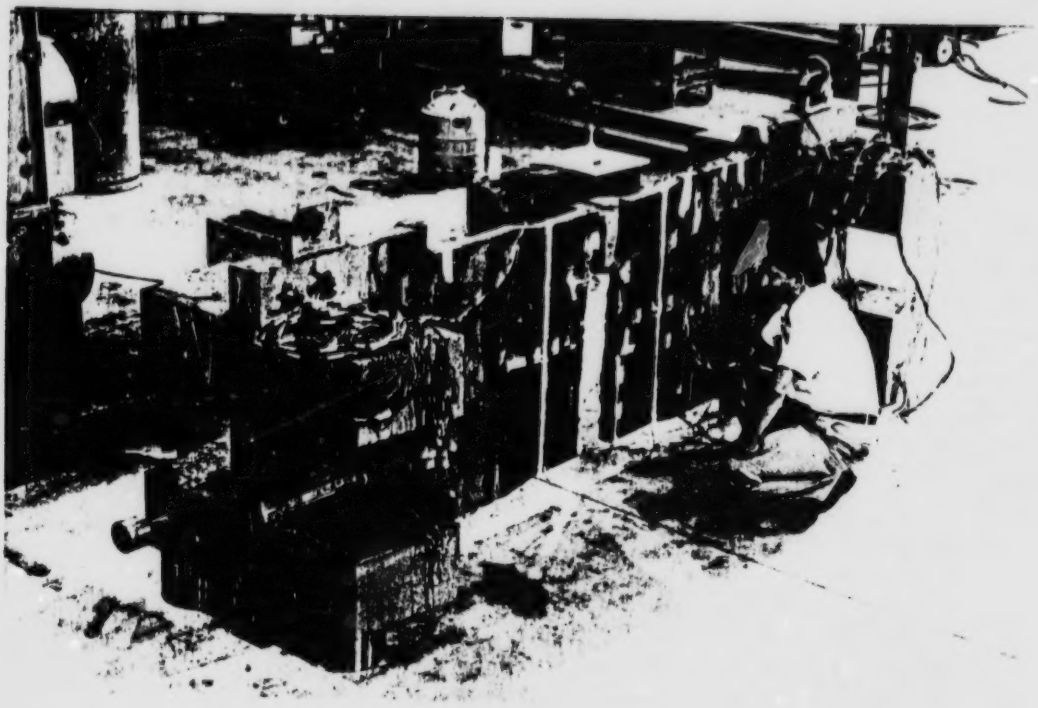


Figure 16. Full view of a fractured wide plate in test #2.

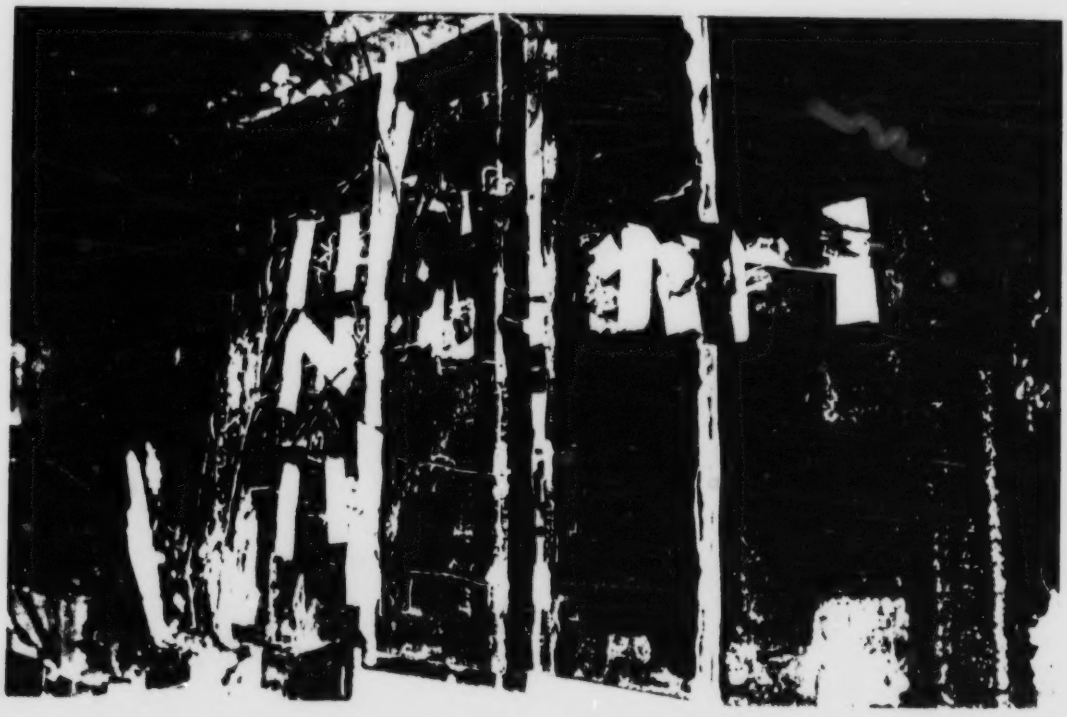
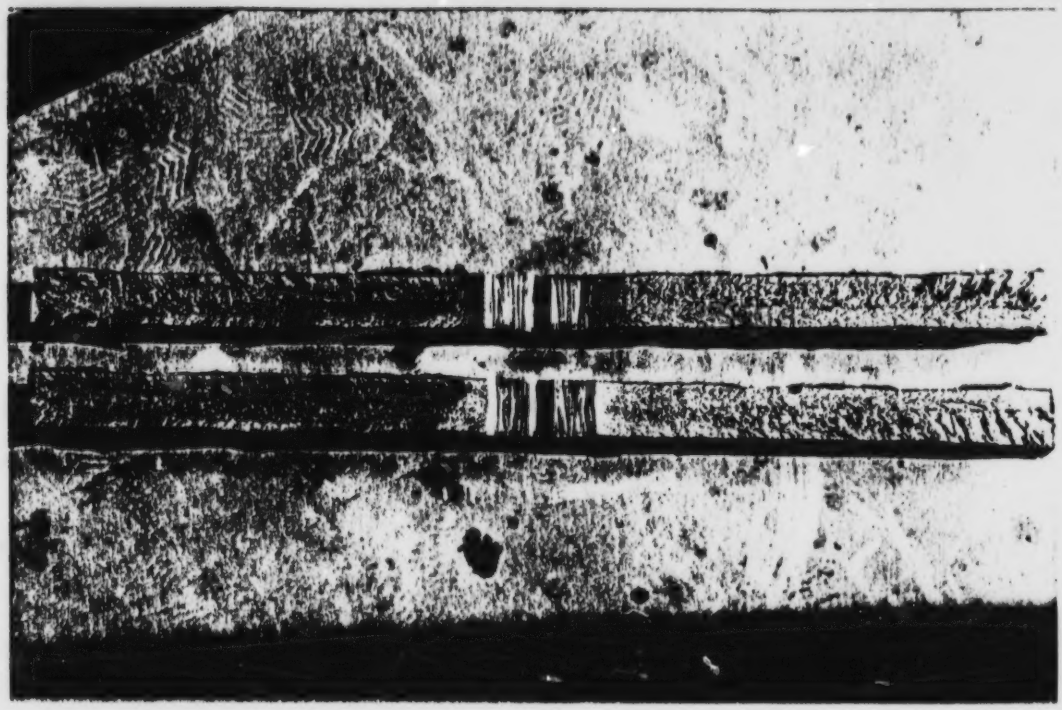


Figure 17. Fracture of wide plate in test #3.



(a)

(b)

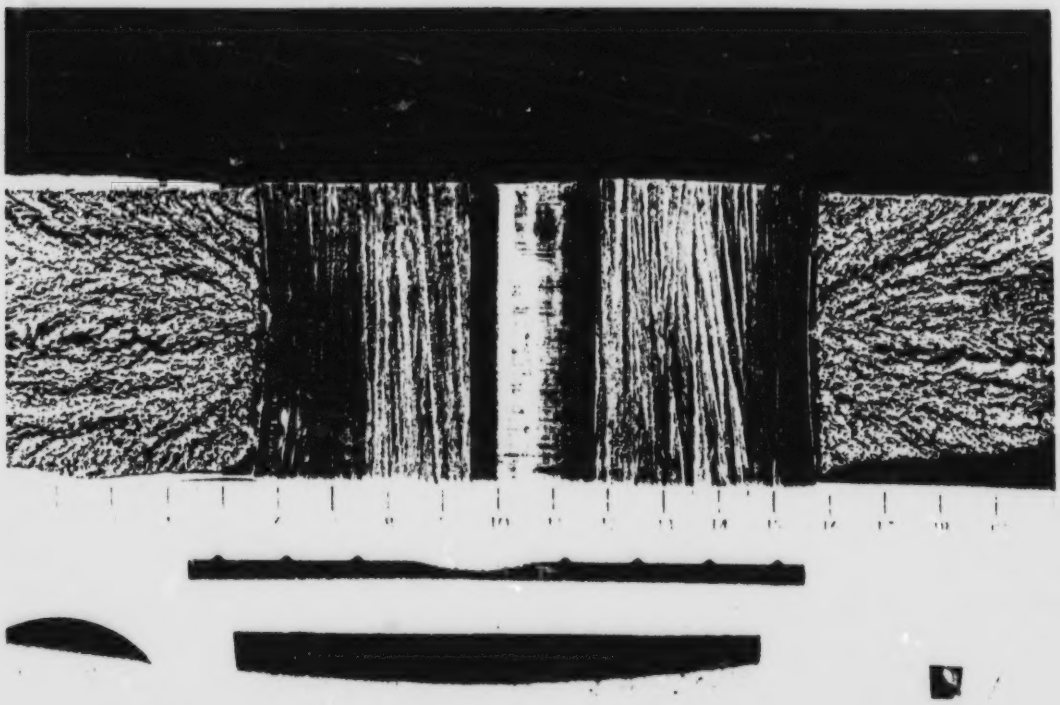


Figure 18. (a) The fracture surfaces of the wide plate failed in test #3.

(b) The fracture surface showing the saw cut defect, the ductile tear and the brittle fracture region.

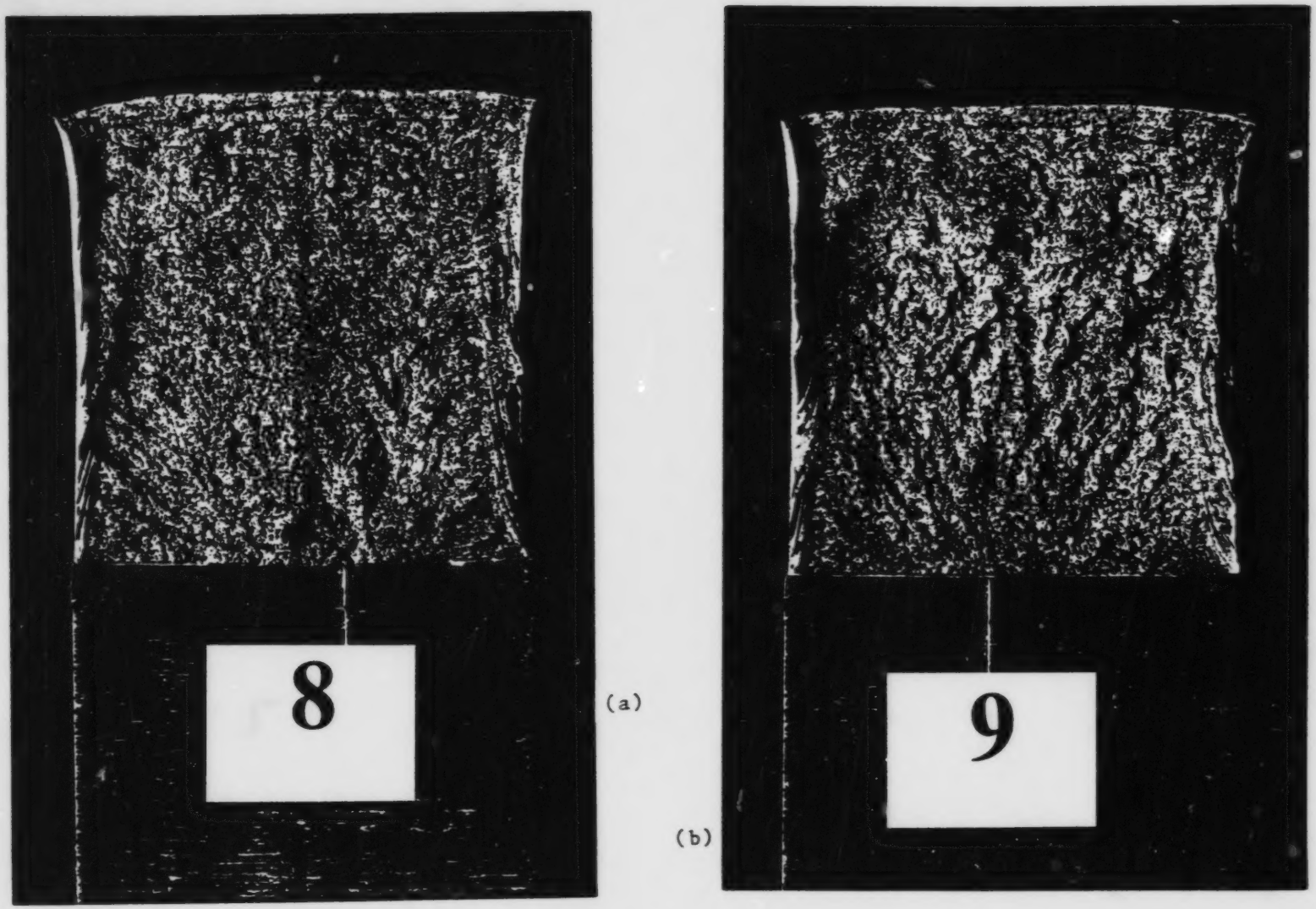


Figure 19. Fracture surfaces of the CTOD specimens with saw cut defects tested at -50°C showing the fracture initiation sites closer to the defect tip.
(a) #8 (b) #9 (Table D5).

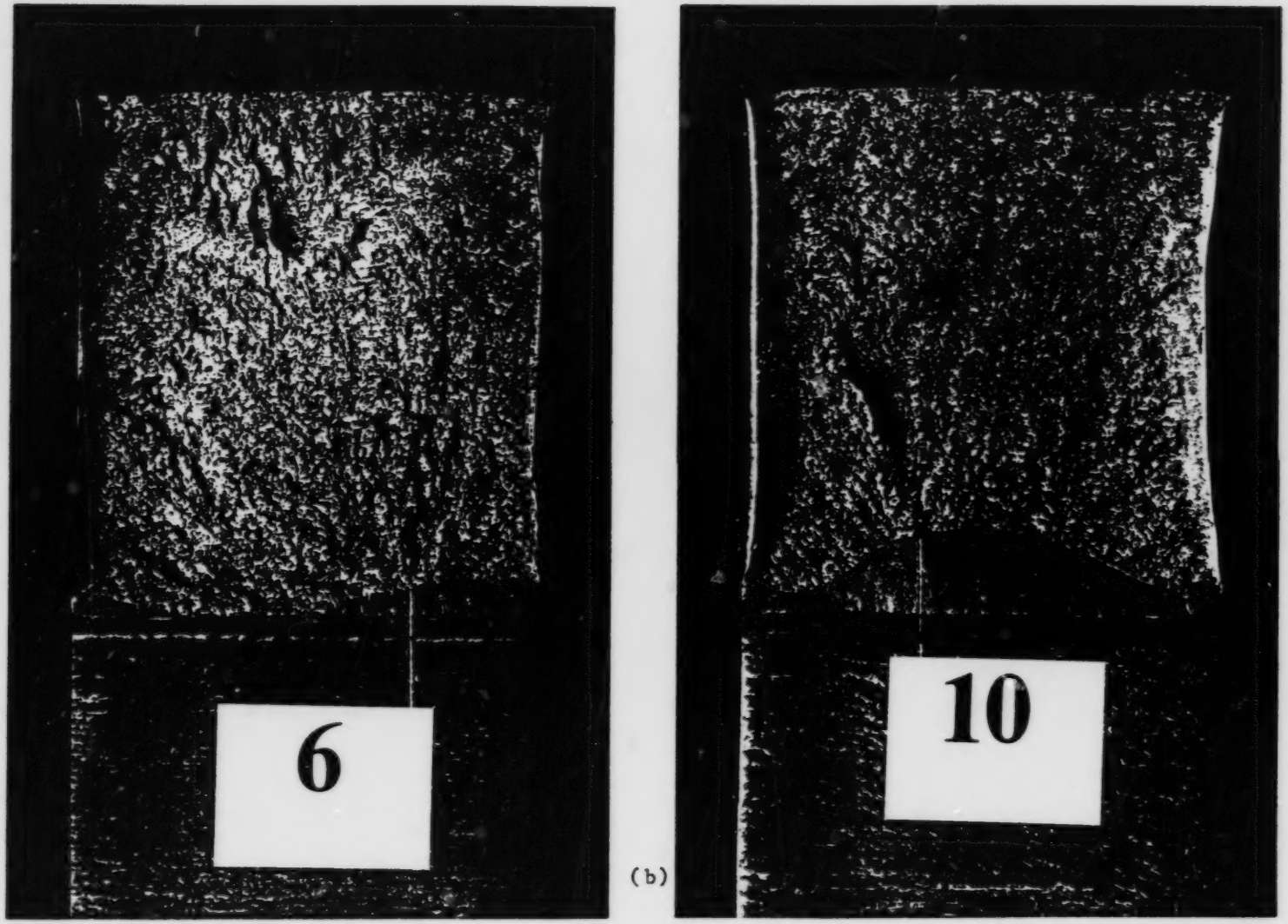


Figure 20. Fracture surfaces of the CTOD specimens with fatigue precrack tested at -50°C showing the fracture initiation sites closer to the fatigue precrack: (a) #6 (b) #10 (Table D3).

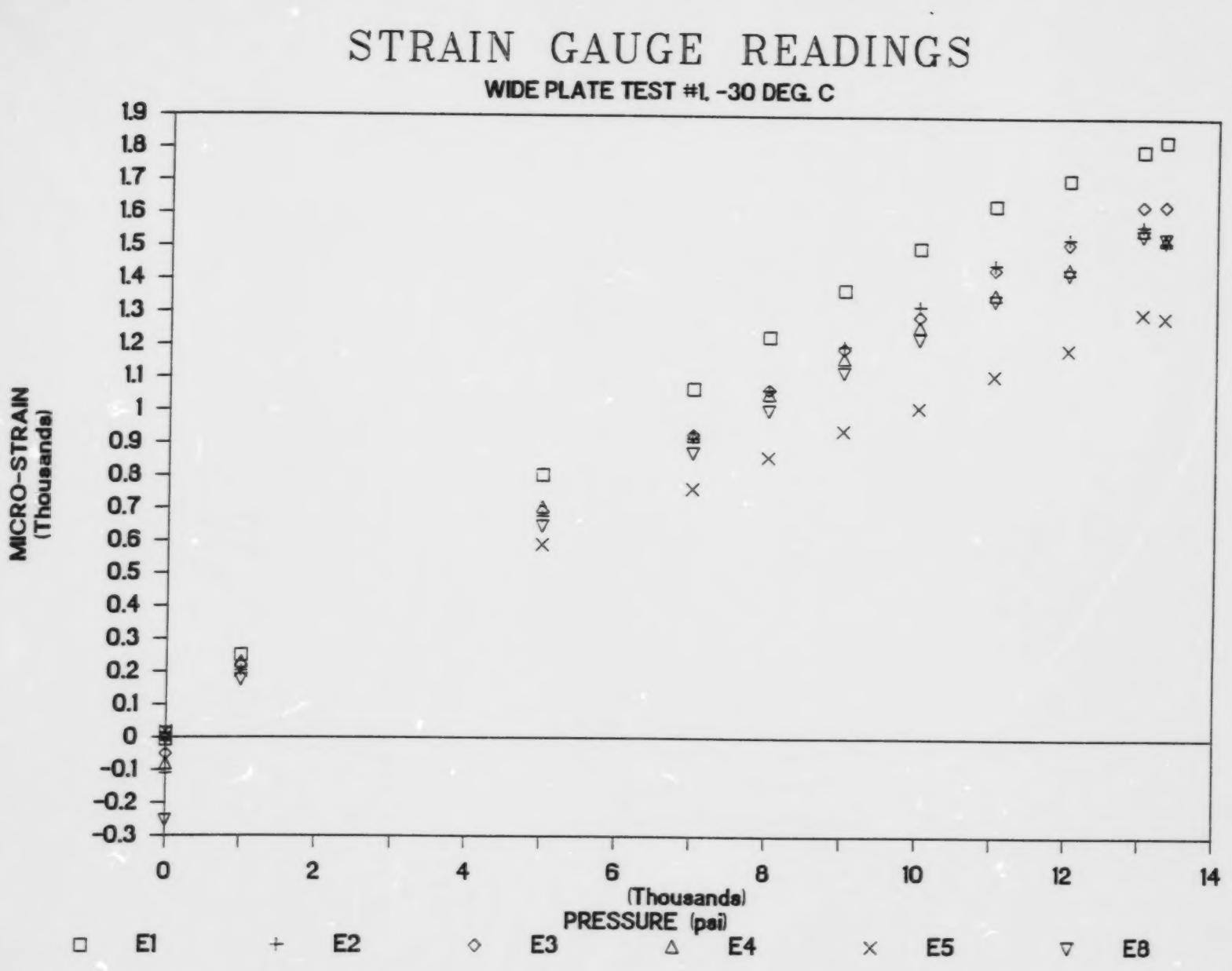


Figure 21a. Strain gauge readings vs Jack pressure plots for Wide Plate Test #1: gauges E1-E5 and E8.

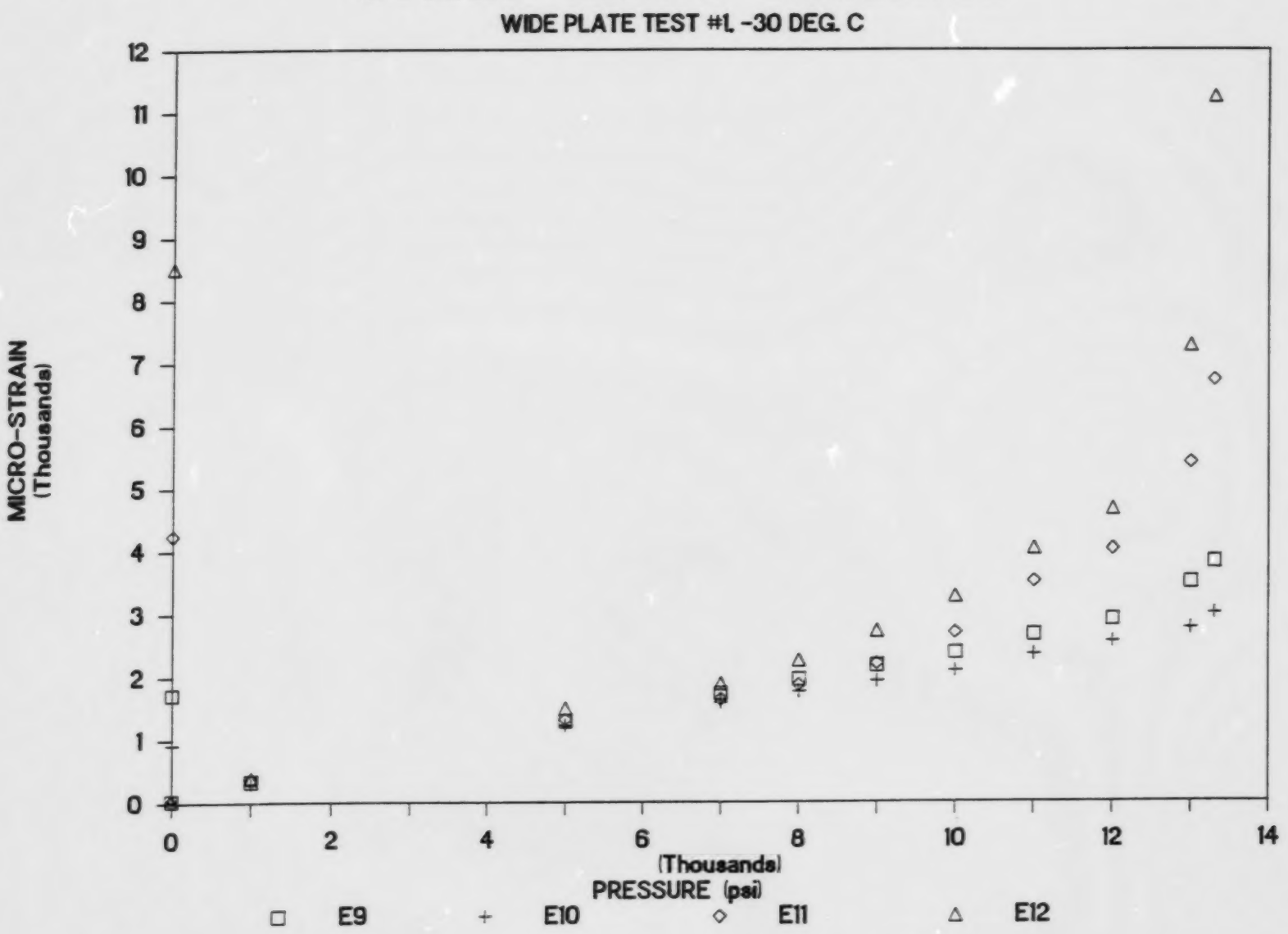


Figure 21b. Strain gauge readings vs Jack pressure plots for Wide Plate Test #1: gauges E9-E12.

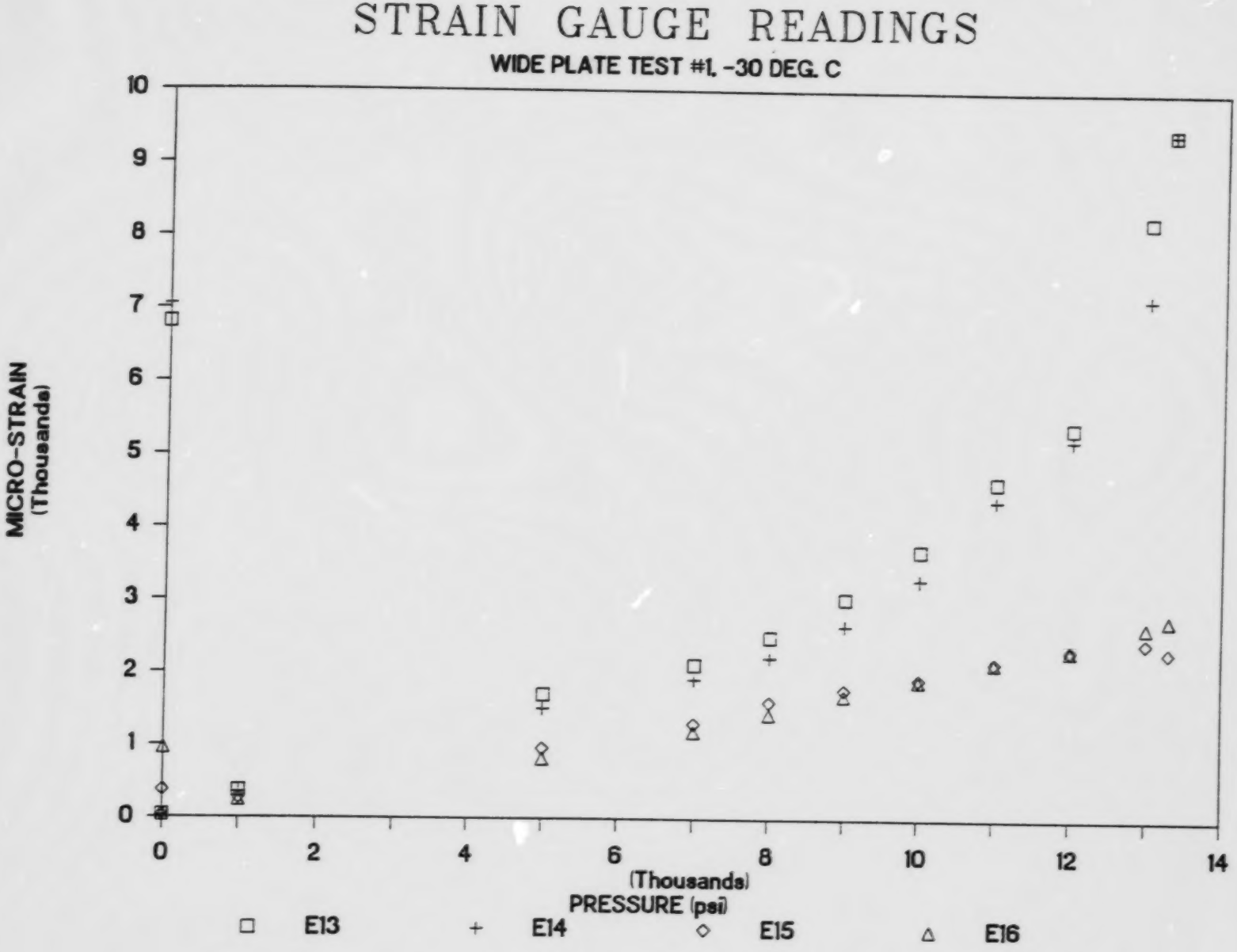


Figure 21c. Strain gauge readings vs Jack pressure plots for wide plate test #1: gauges E13-E16.

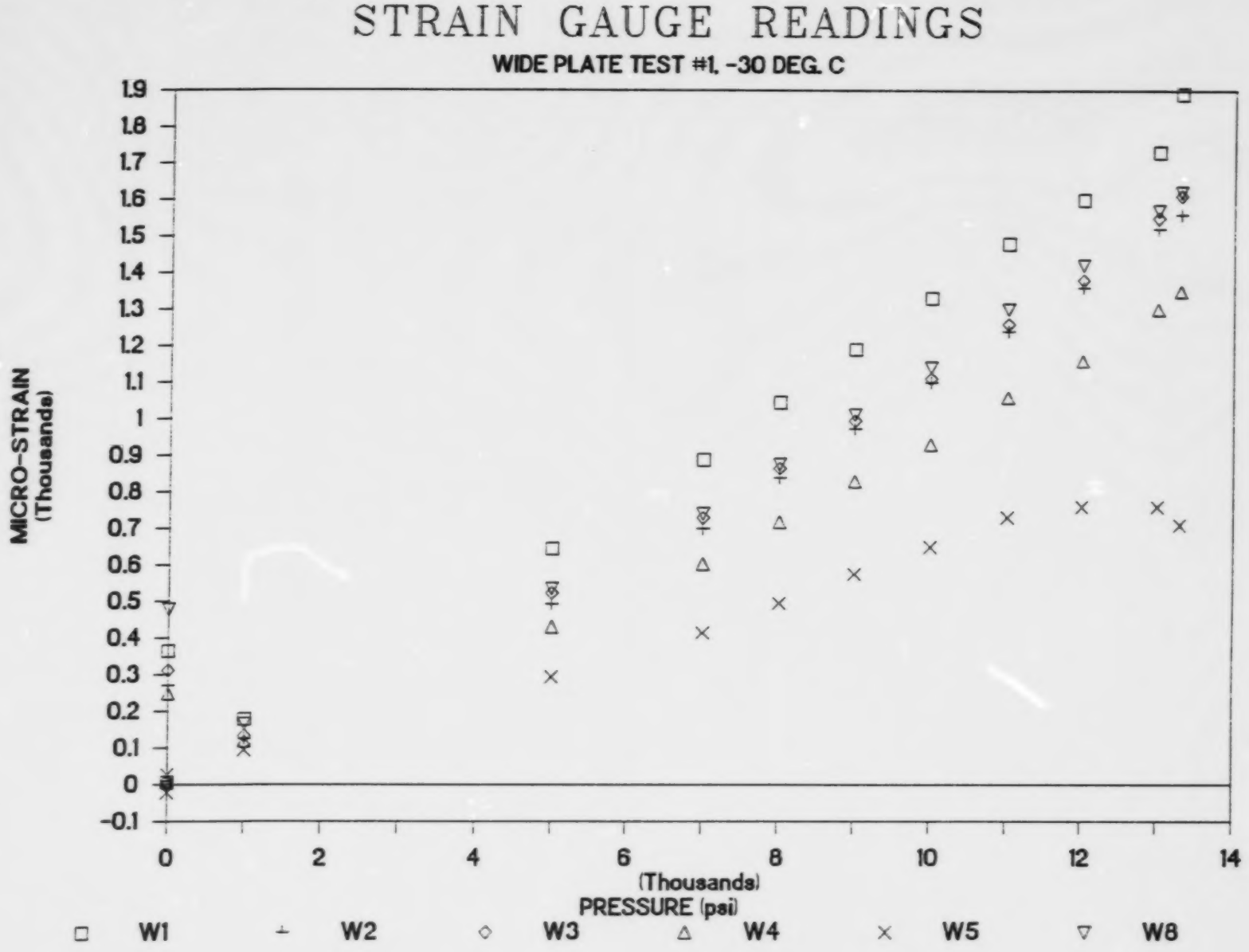


Figure 21d. Strain gauge readings vs Jack pressure plots for wide plate test #1: gauges W1-W5 and W8.

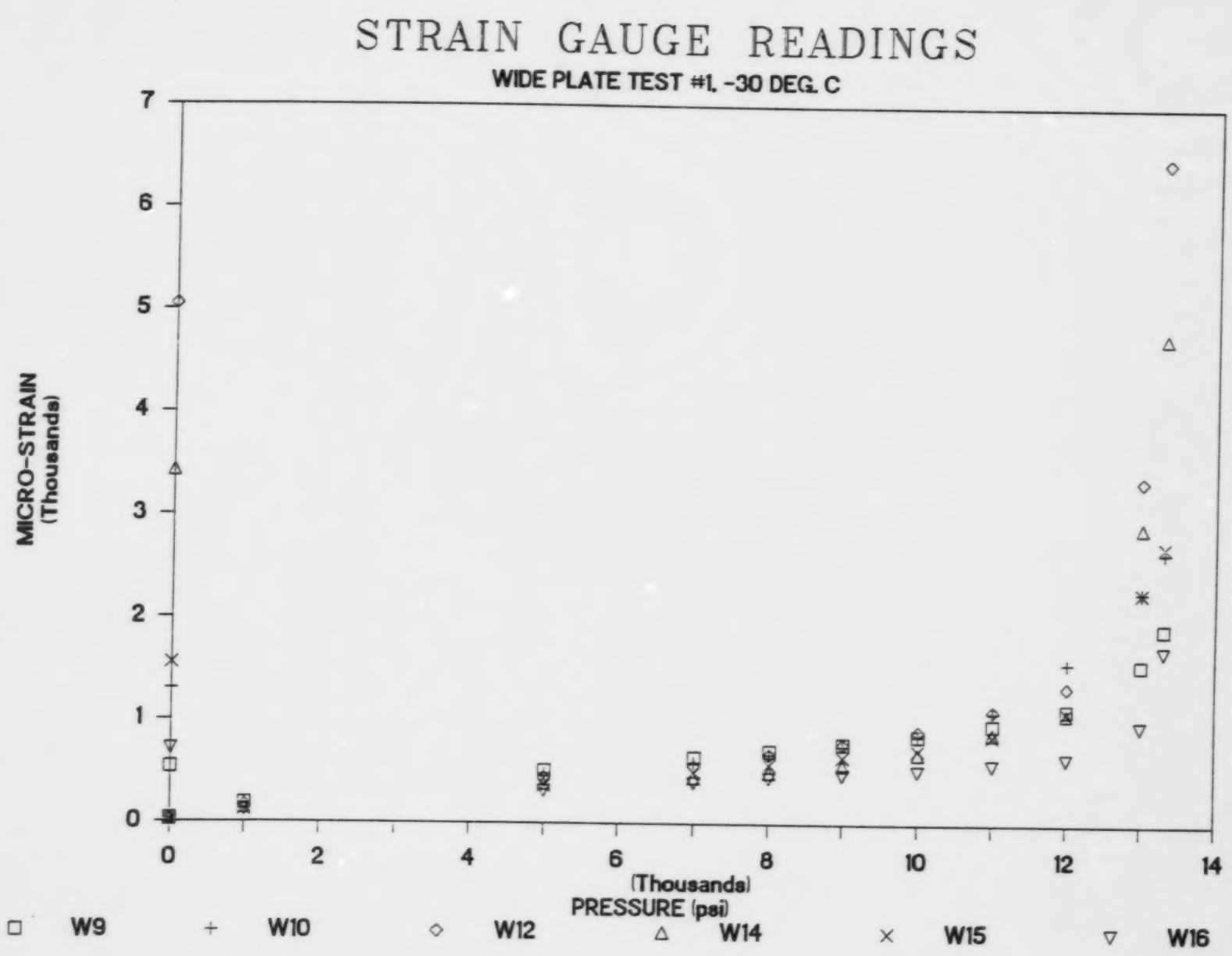


Figure 21e. Strain gauge readings vs Jack pressure for plots for wide plate test #1: gauges W9, W10, W12 and W14-W16.

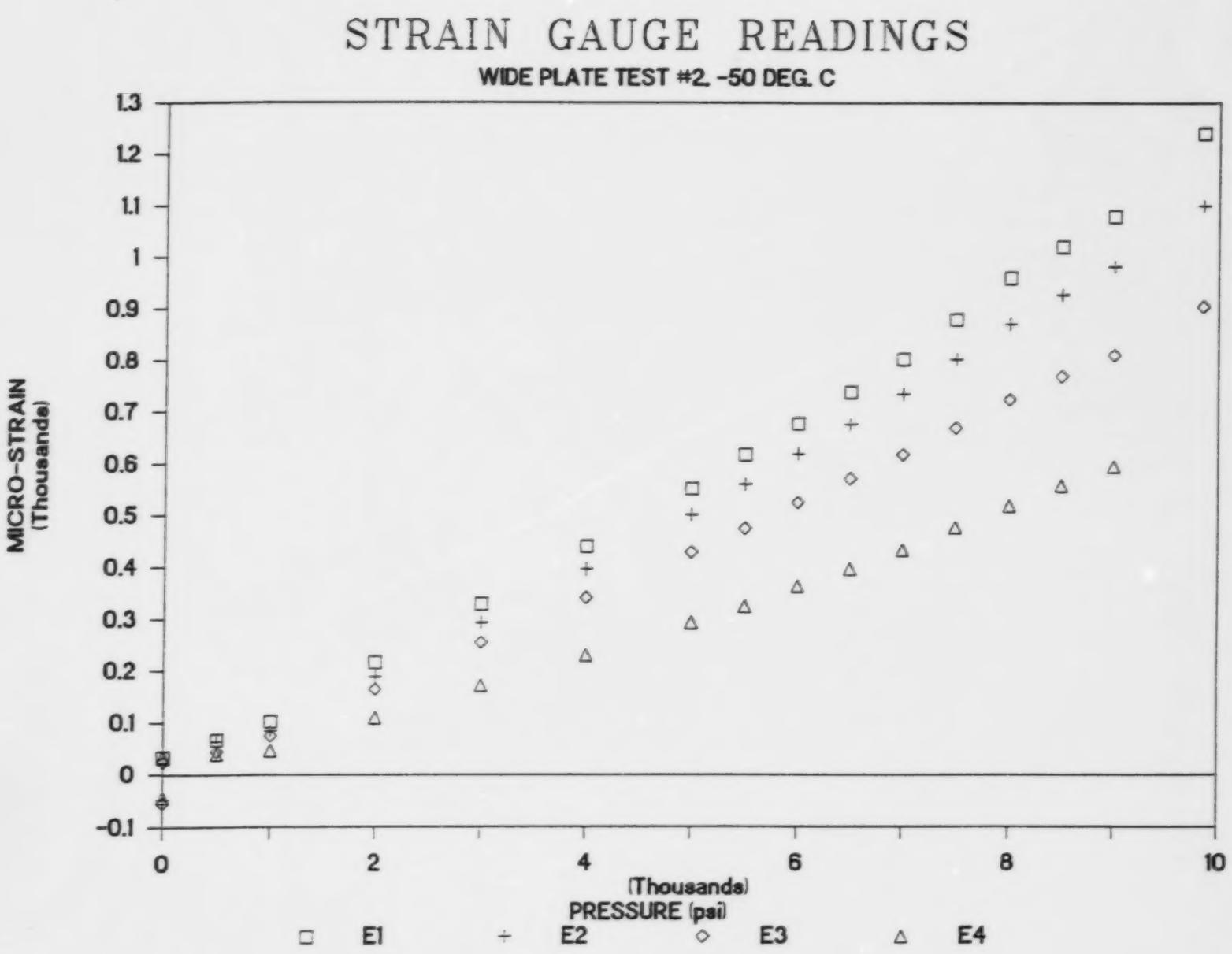


Figure 22a. Strain gauge readings vs Jack pressure plots for wide plate test #2: gauges E1-E4

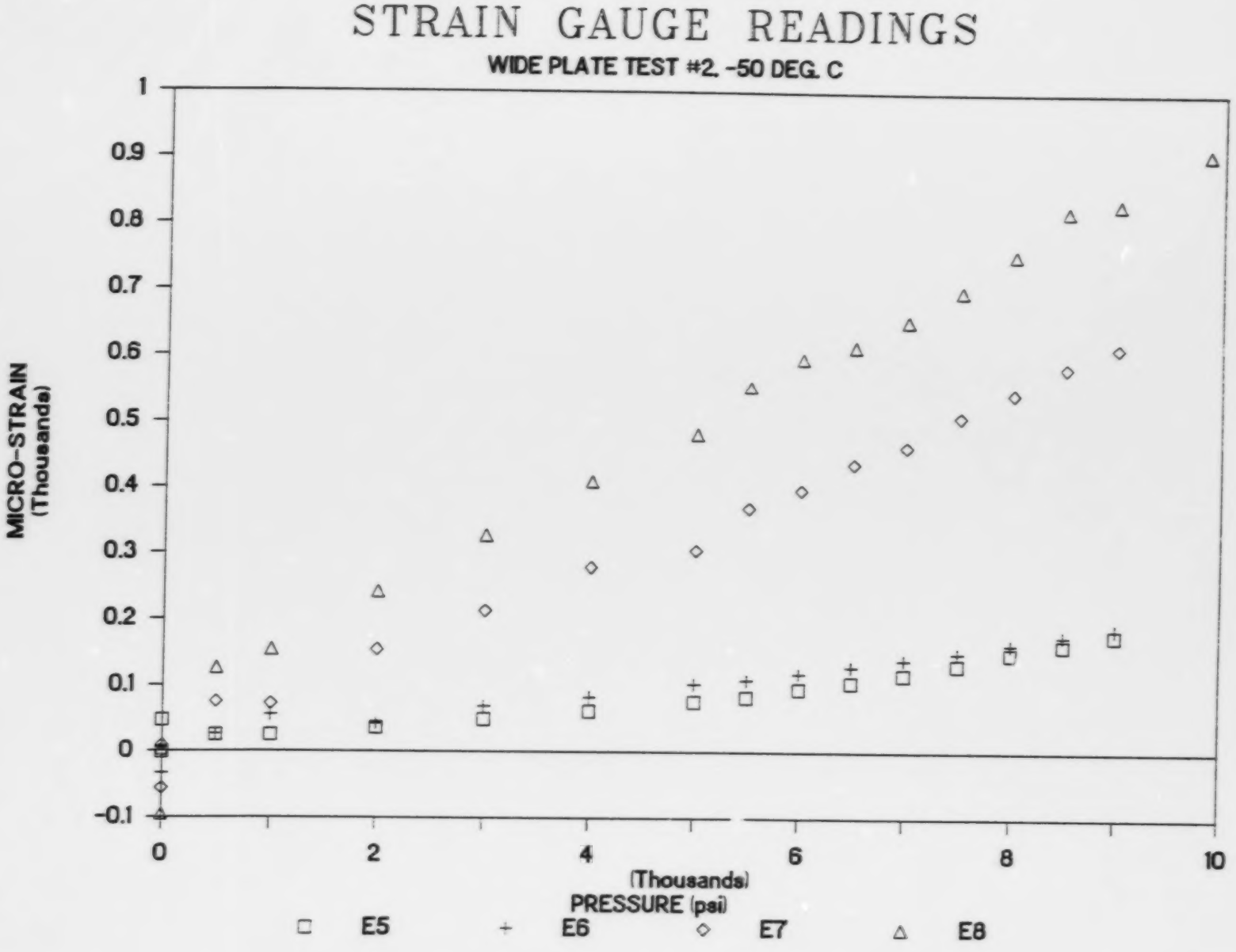


Figure 22b. Strain gauge readings vs Jack pressure plots for wide plate test #2: gauges E5-E8.

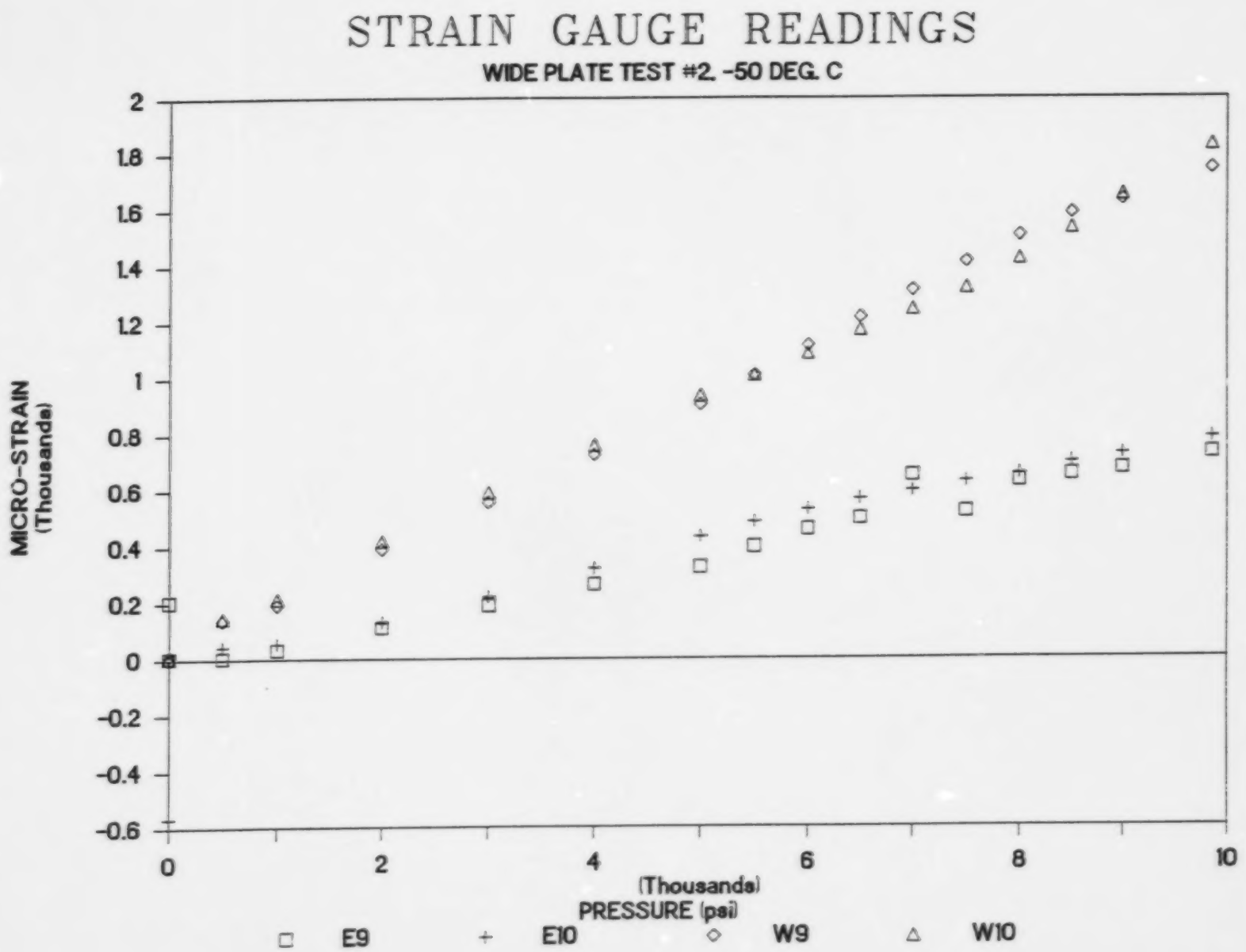


Figure 22c. Strain gauge readings vs Jack pressure plots for wide plate test #2: gauges E9, E10, W9, and W10.

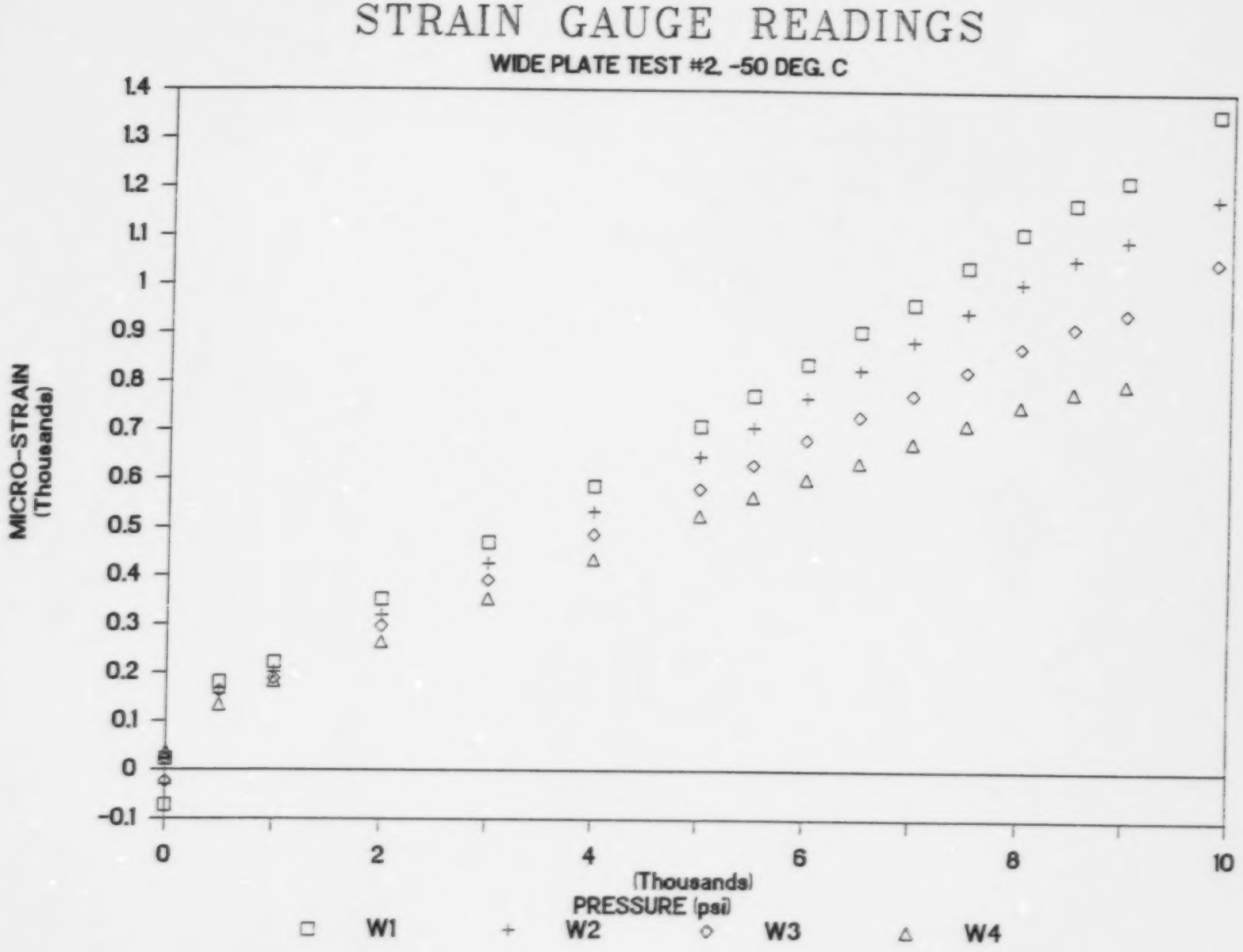


Figure 22d. Strain gauge readings vs Jack pressure plots for wide plate test #2: gauges W1-W4.

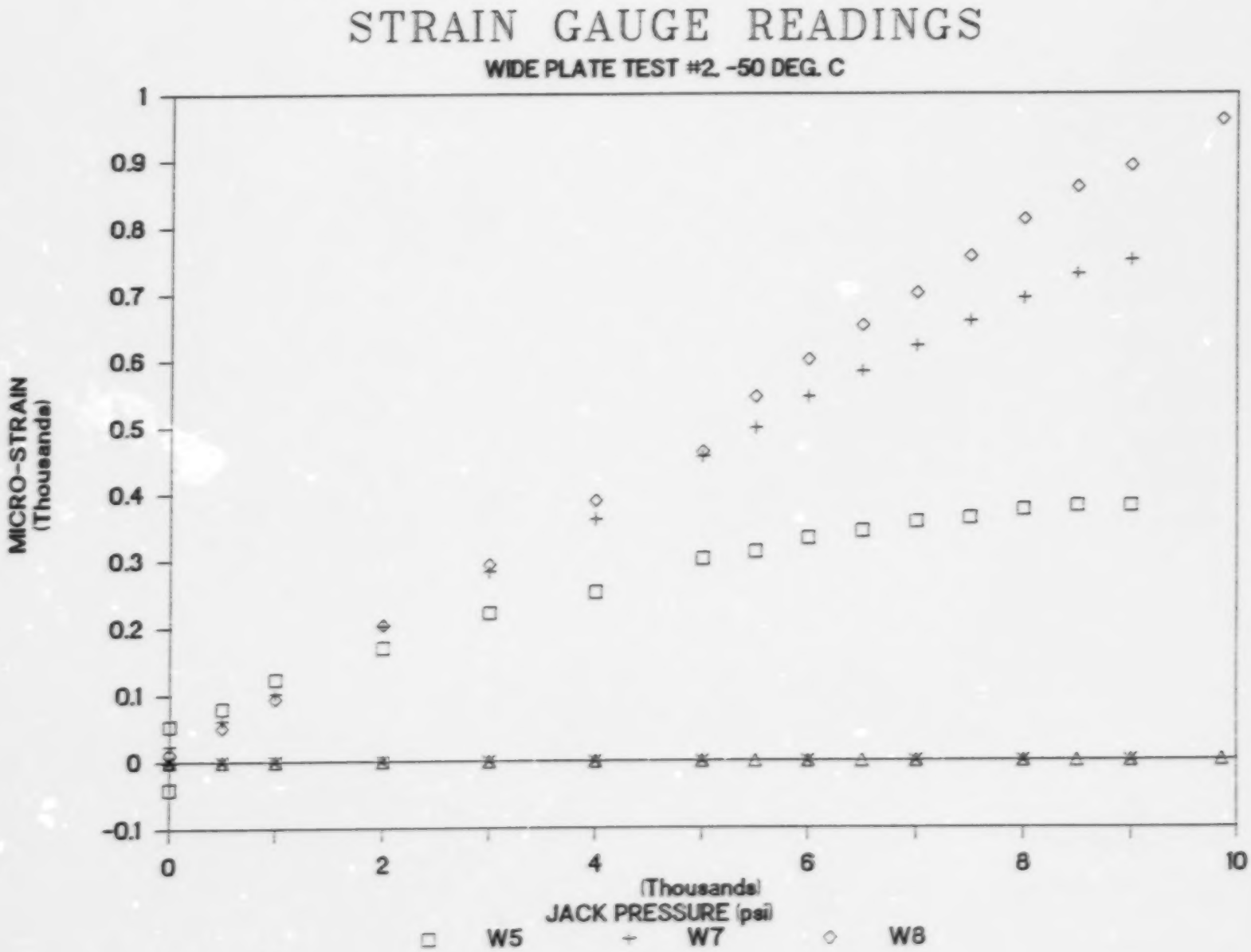


Figure 22e. Strain gauge readings vs Jack pressure plots for wide plate test #2: gauges W5, W7, W8.

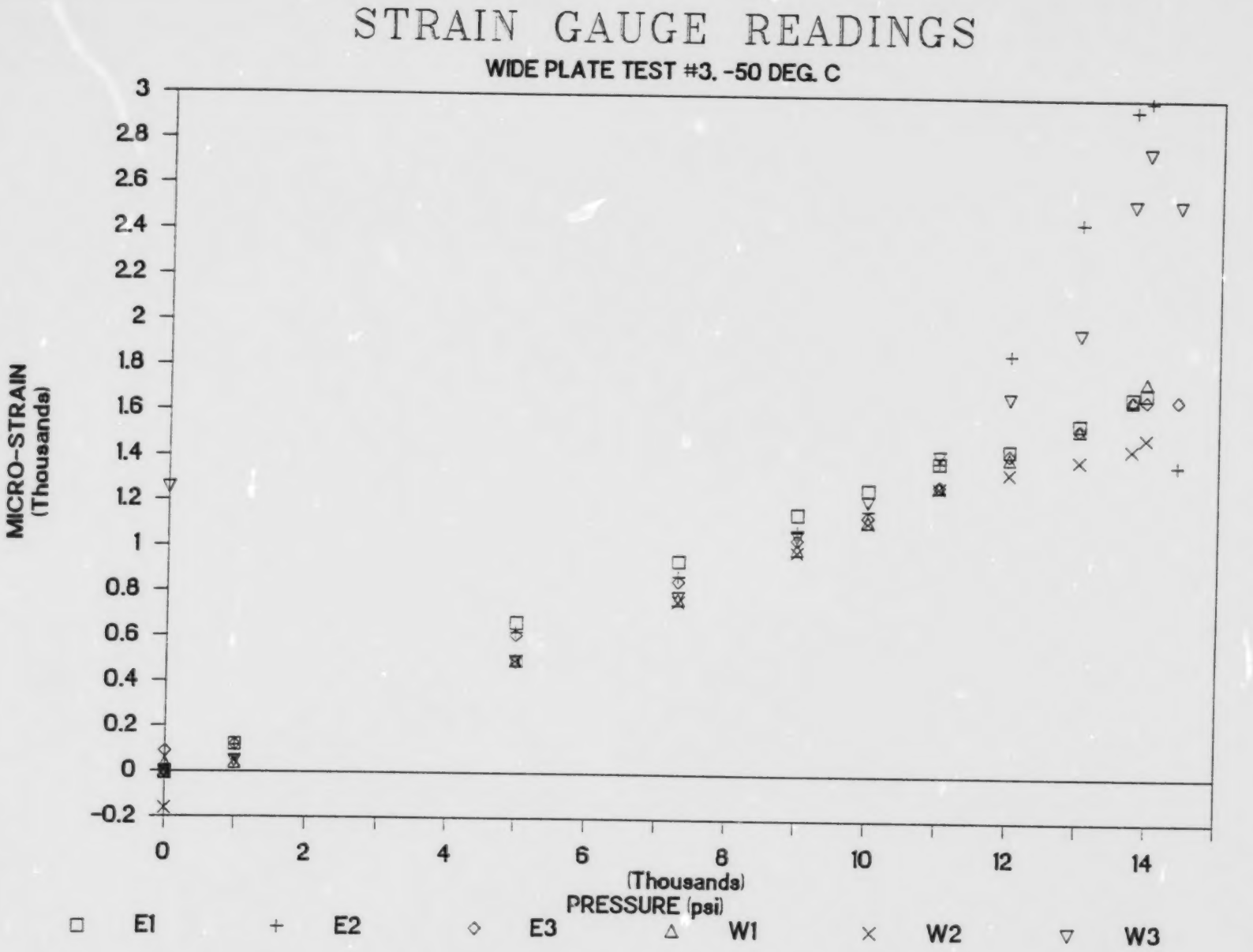


Figure 23a. Strain gauge readings vs Jack pressure plots for wide plate test #3: gauges E1-E3 and W1-W3.

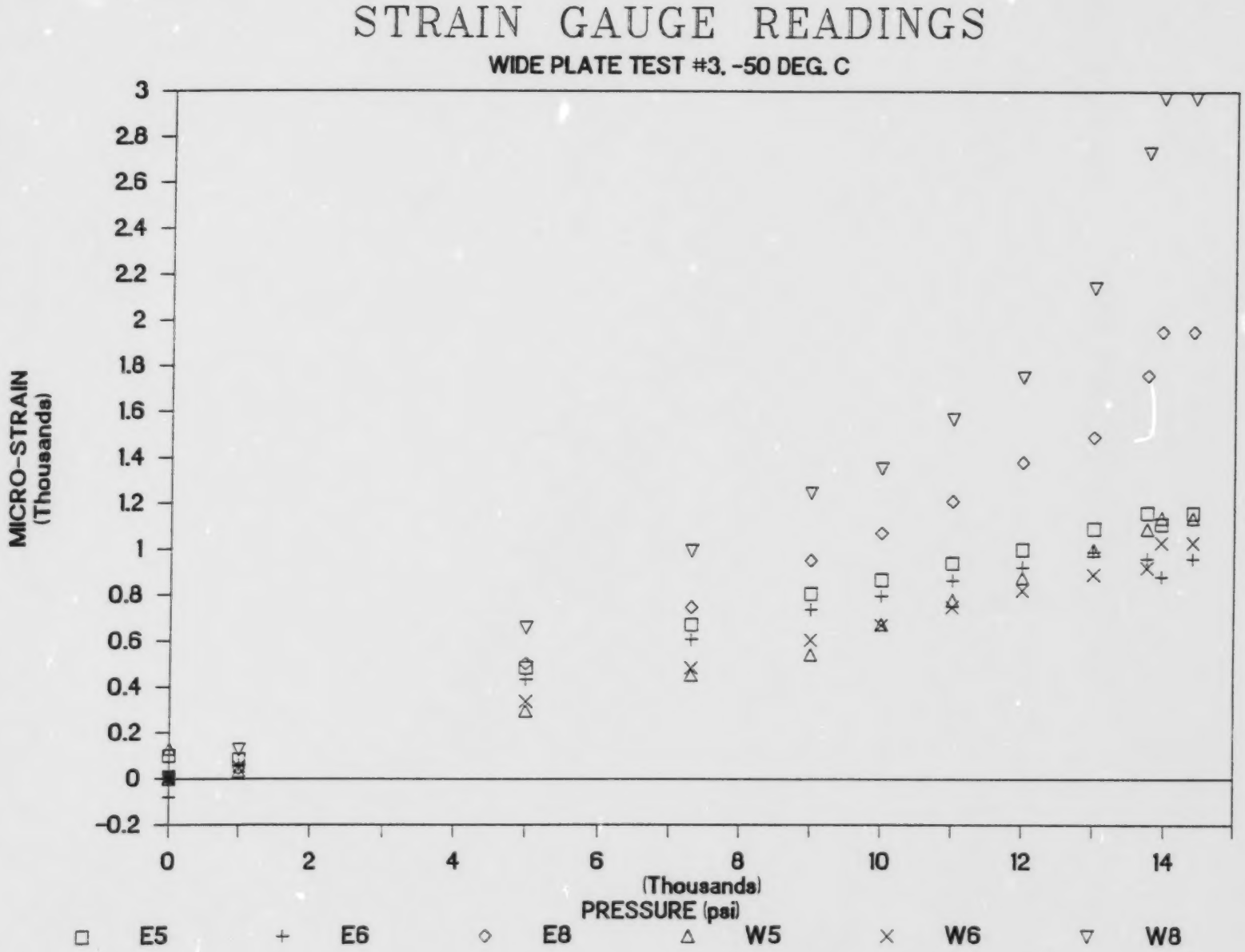


Figure 23b. Strain gauge readings vs Jack pressure plots for wide plate test #3: gauges E5, E6, E8, W5, W6 and W8.

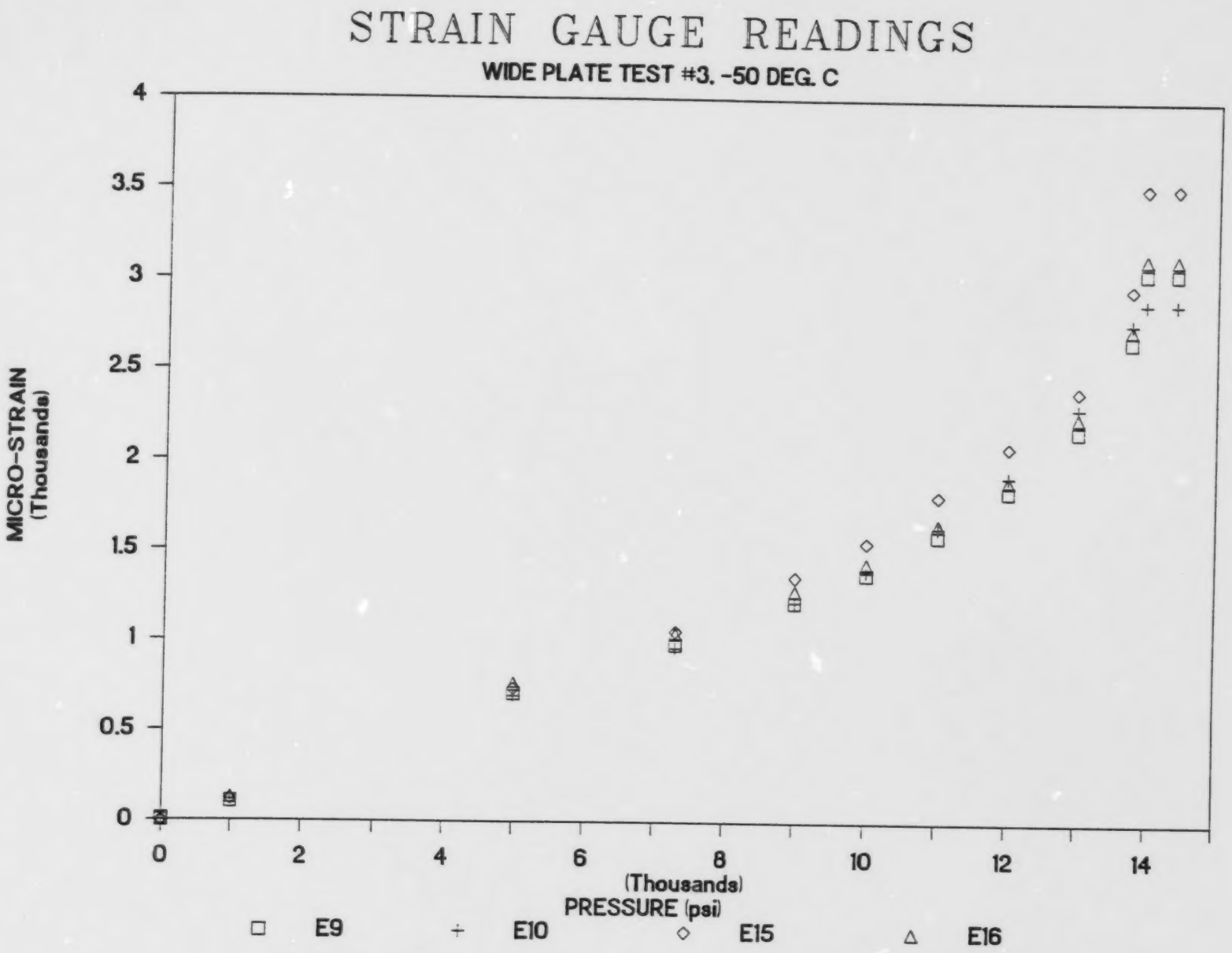


Figure 23c. Strain gauge readings vs Jack pressure plots for wide plate test #3: gauges E9, E10, E15, and E16.

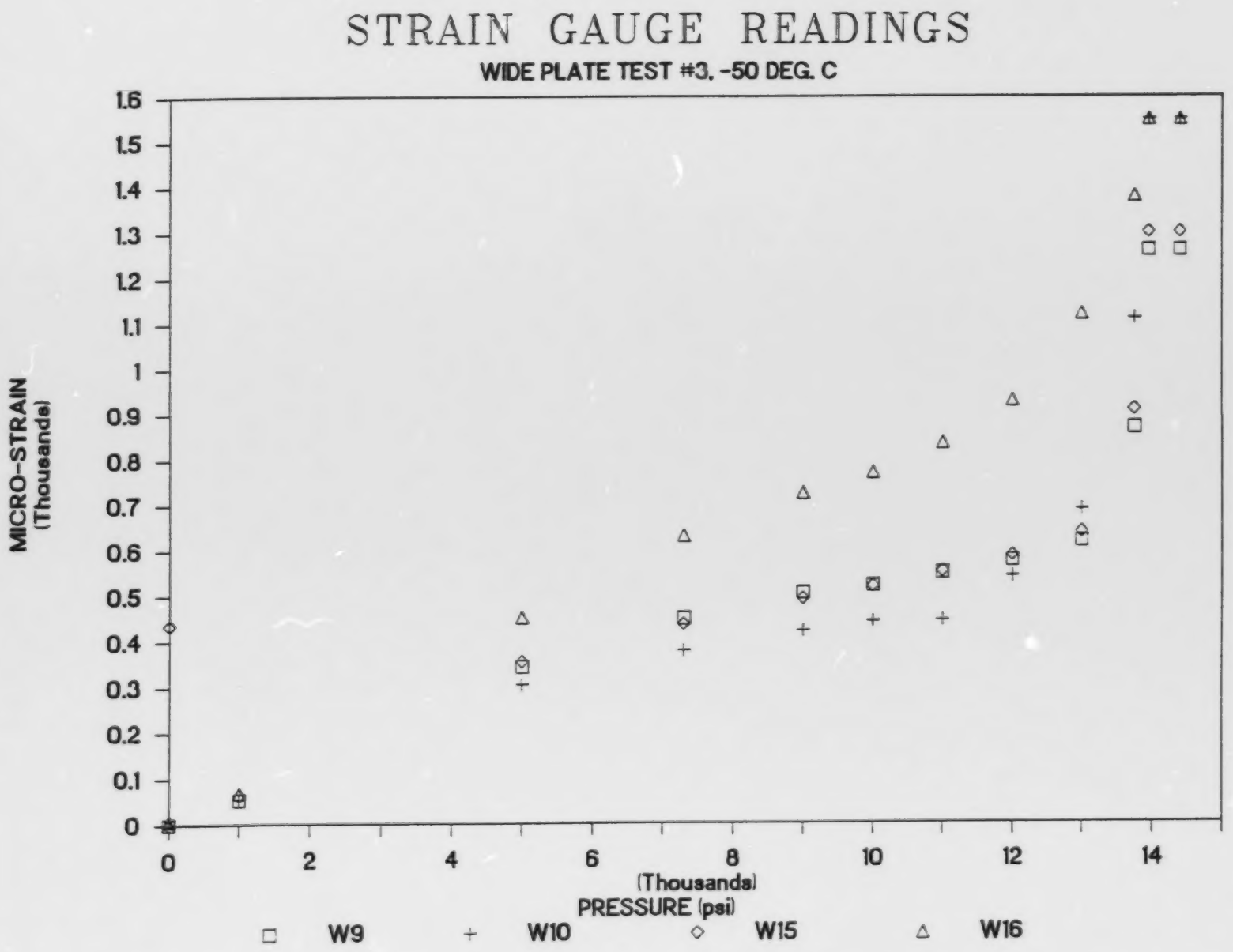


Figure 23d. Strain gauge readings vs Jack pressure plots for wide plate test #3: gauges W9, W10, W15 and W16.

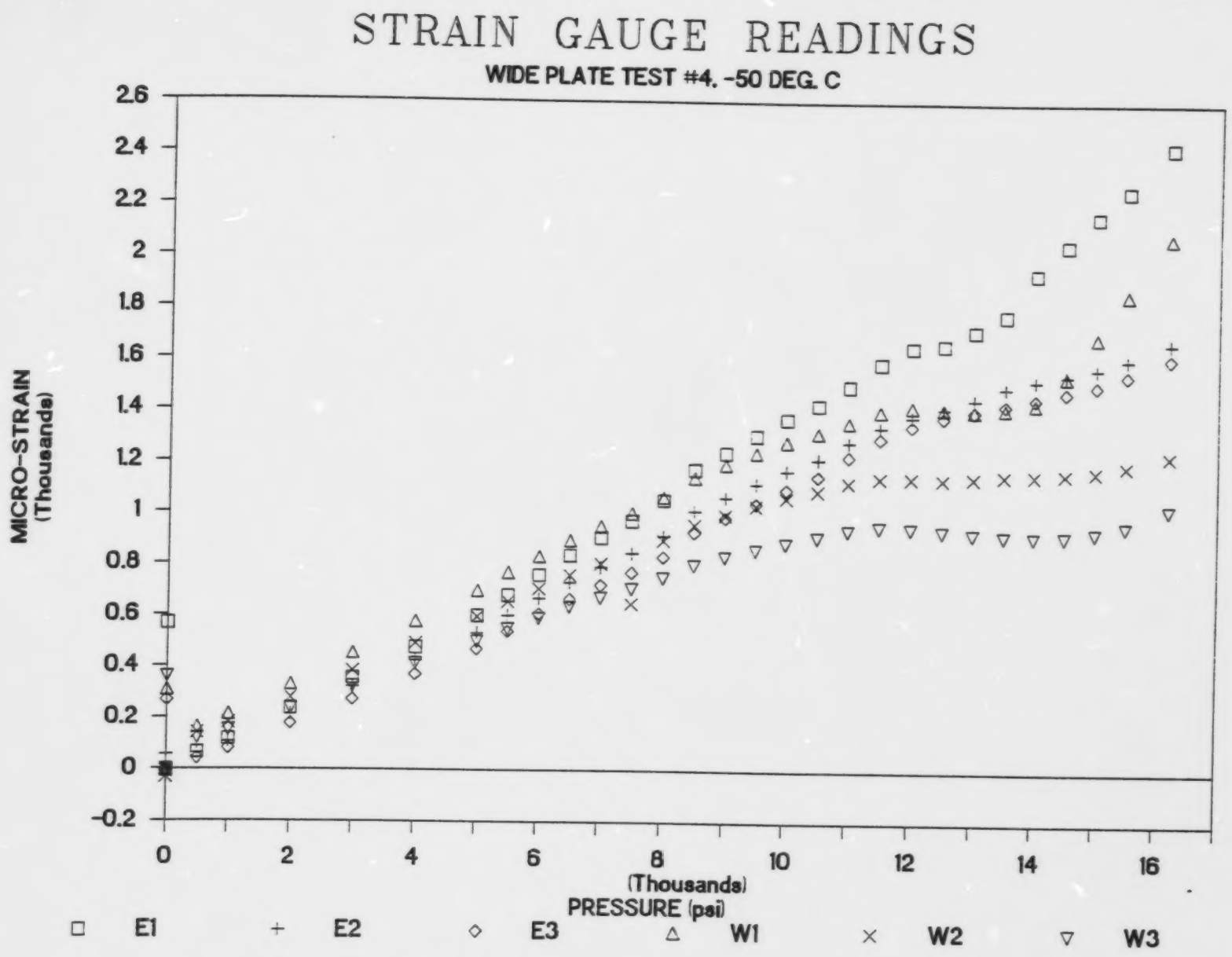


Figure 24a. Strain gauge readings vs Jack pressure plots for wide plate test #4: gauges E1-E3 and W1-W3.

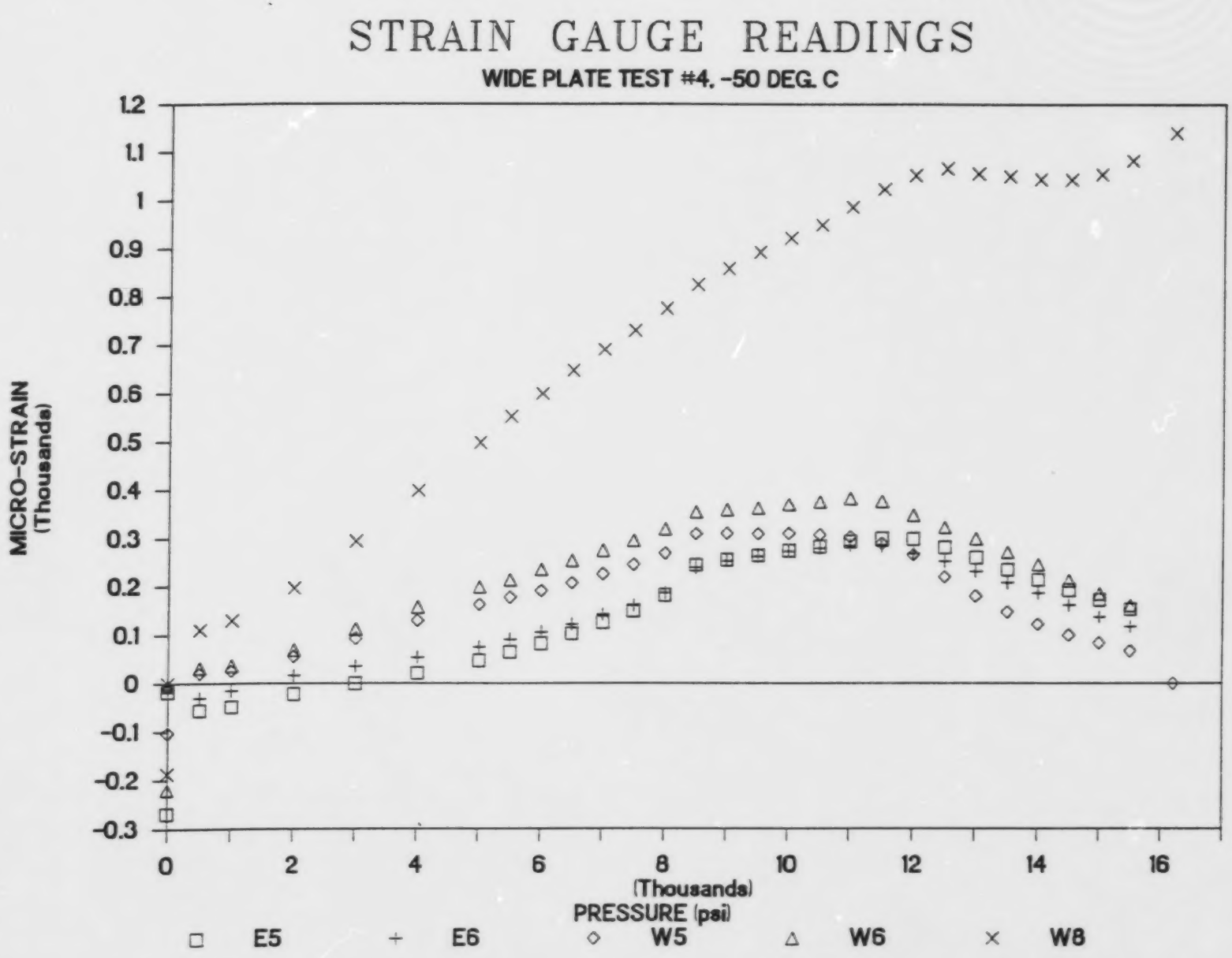


Figure 24b. Strain gauges readings vs Jack pressure plots for wide plate test #4: gauges E5, E6, W5, W6 and W8.

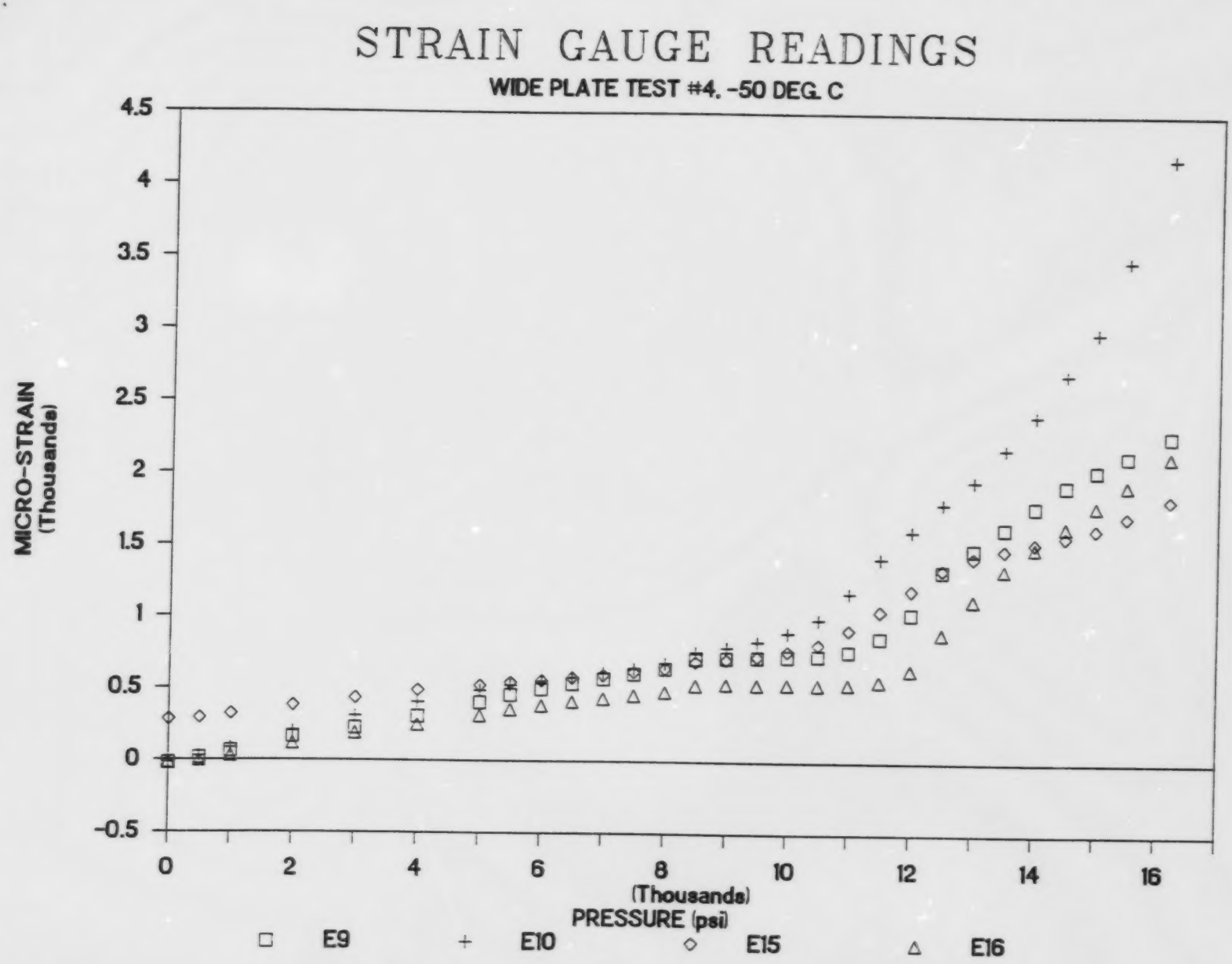


Figure 24c. Strain gauge readings vs Jack pressure plots for wide plate test #4: gauges E9, E10 and E15 and E16.

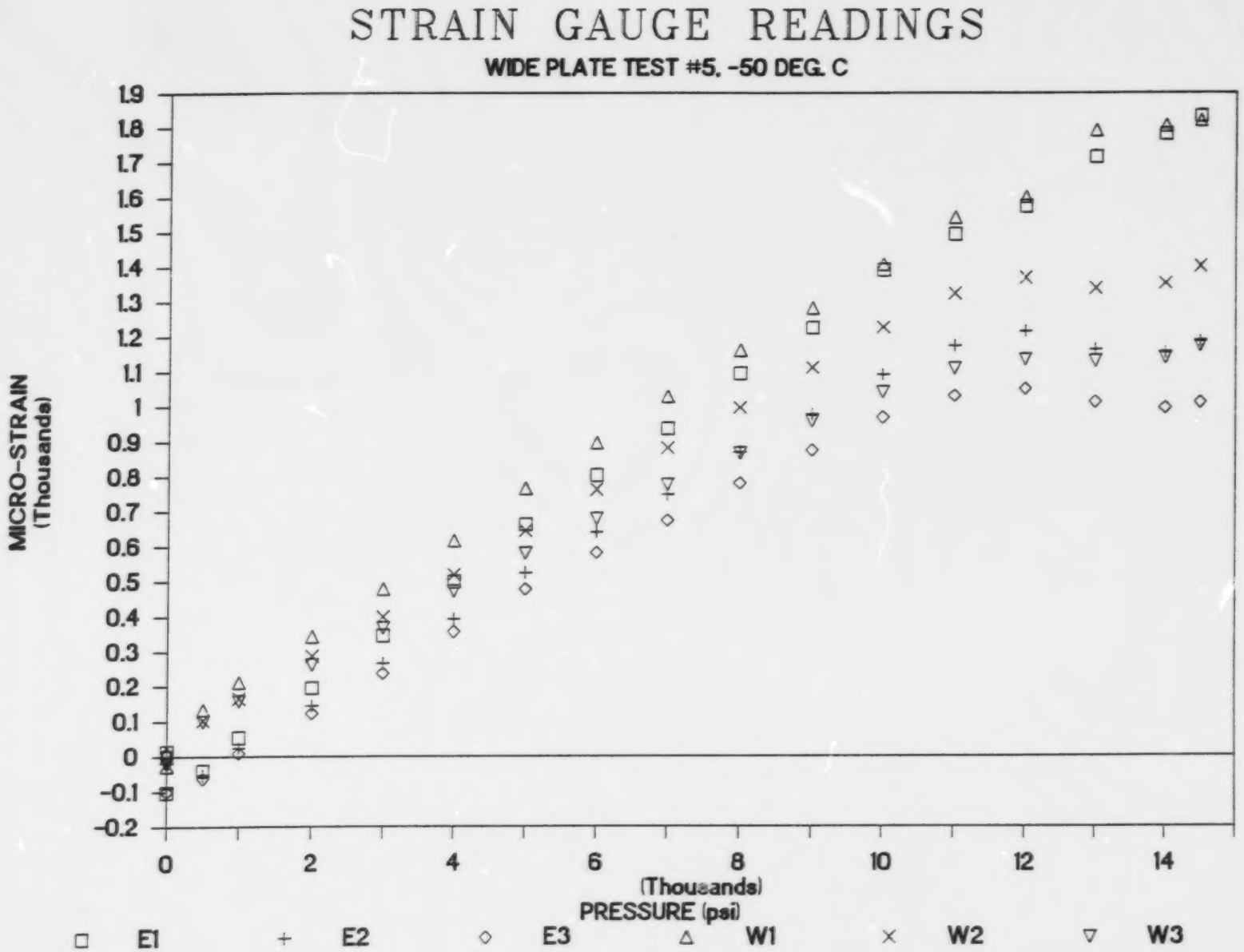


Figure 25a. Strain gauge readings vs Jack pressure plots for wide plate test #5: gauges E1-E3 and W1-W3.

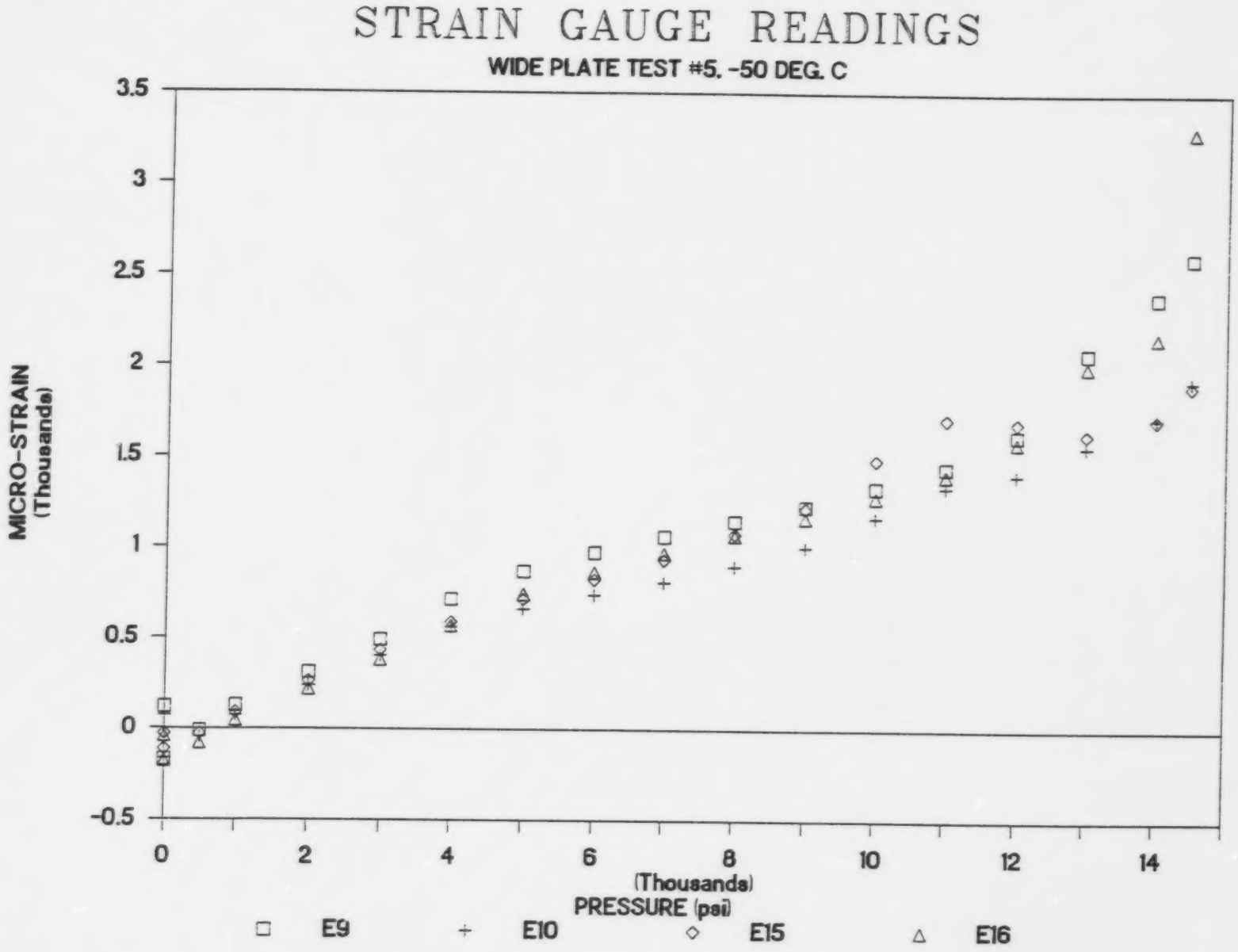


Figure 25b. Strain gauge readings vs Jack pressure plots for wide plate test #5: gauges E9, E10, E15 and E16.

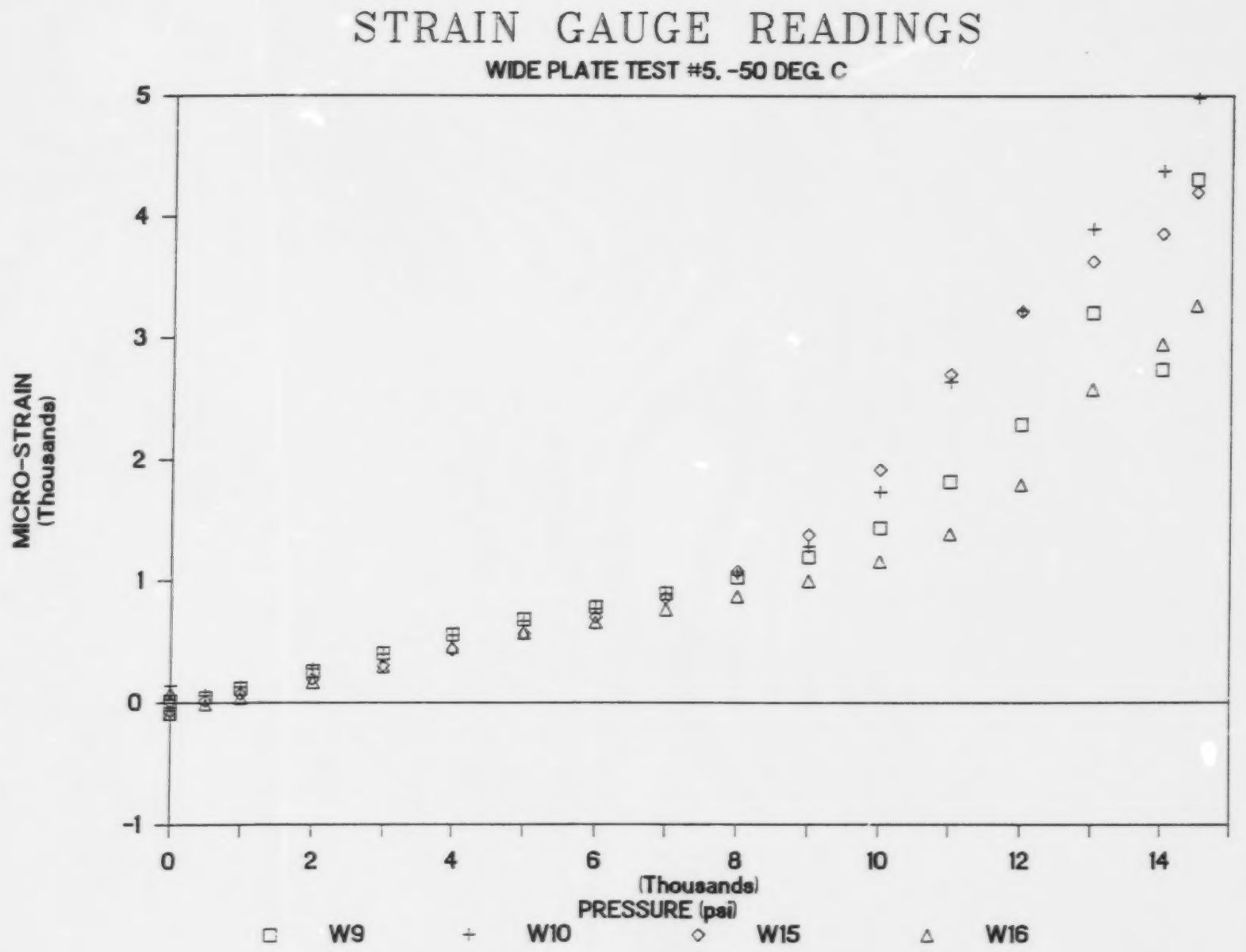


Figure 25c. Strain gauge readings vs Jack pressure plots for wide plate test #5: gauges W9, W10, W15 and W16.

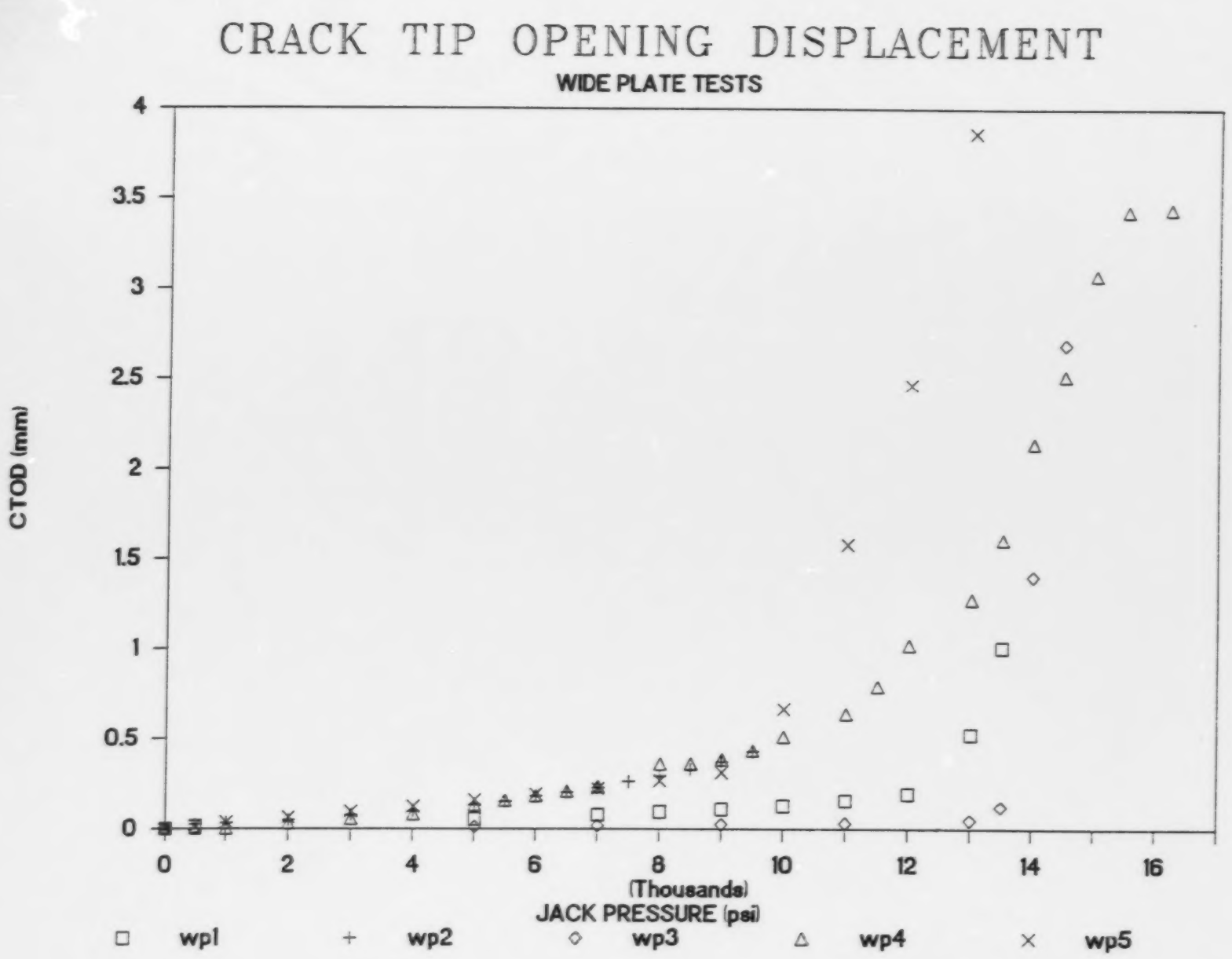


Figure 26. The crack tip opening displacement vs jack pressure plots.

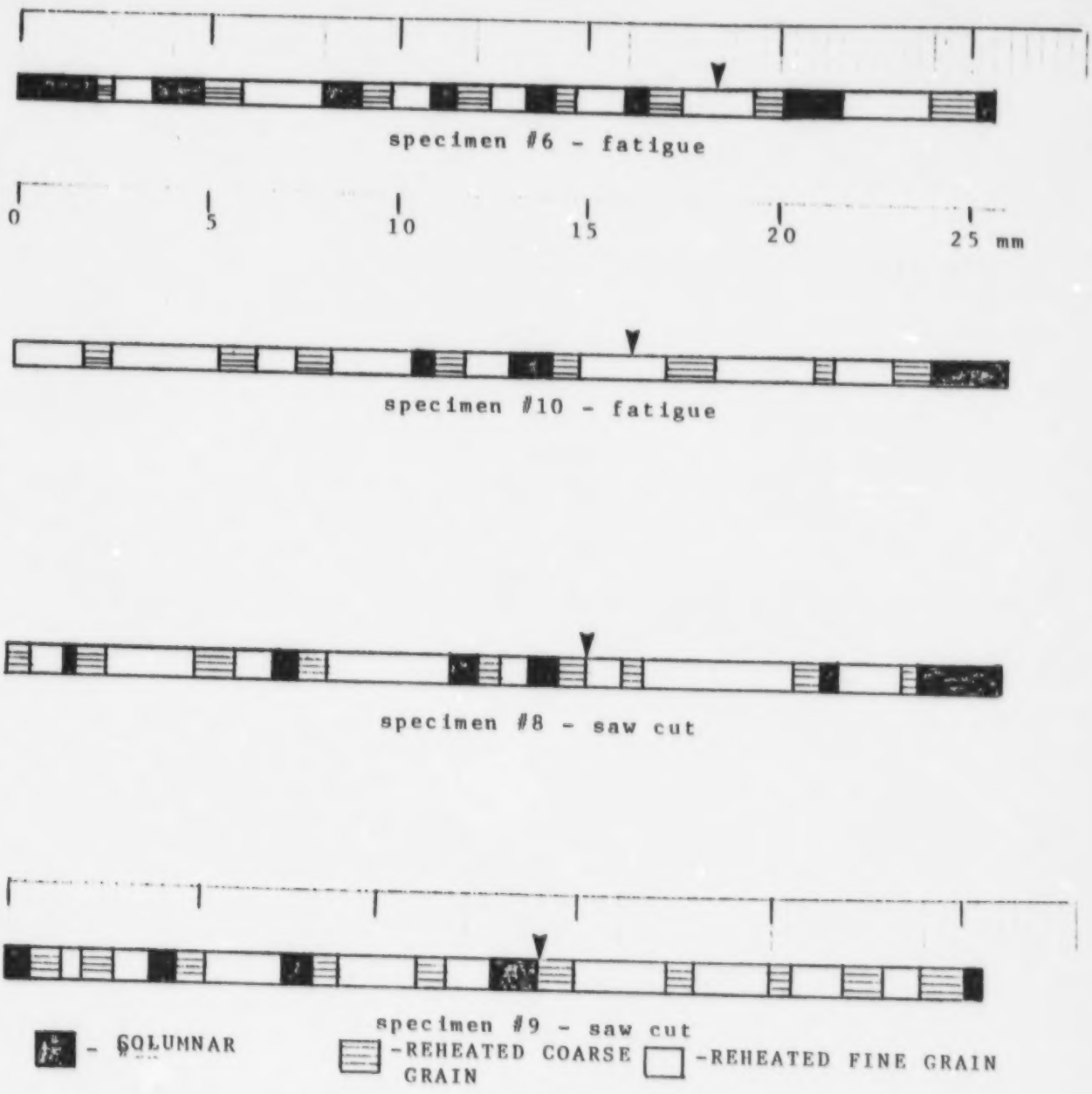


Figure 27. The weld metal microstructures sampled by the defect tips of 25 x 50mm CTOD specimens. Arrow shows approximate fracture initiation site.

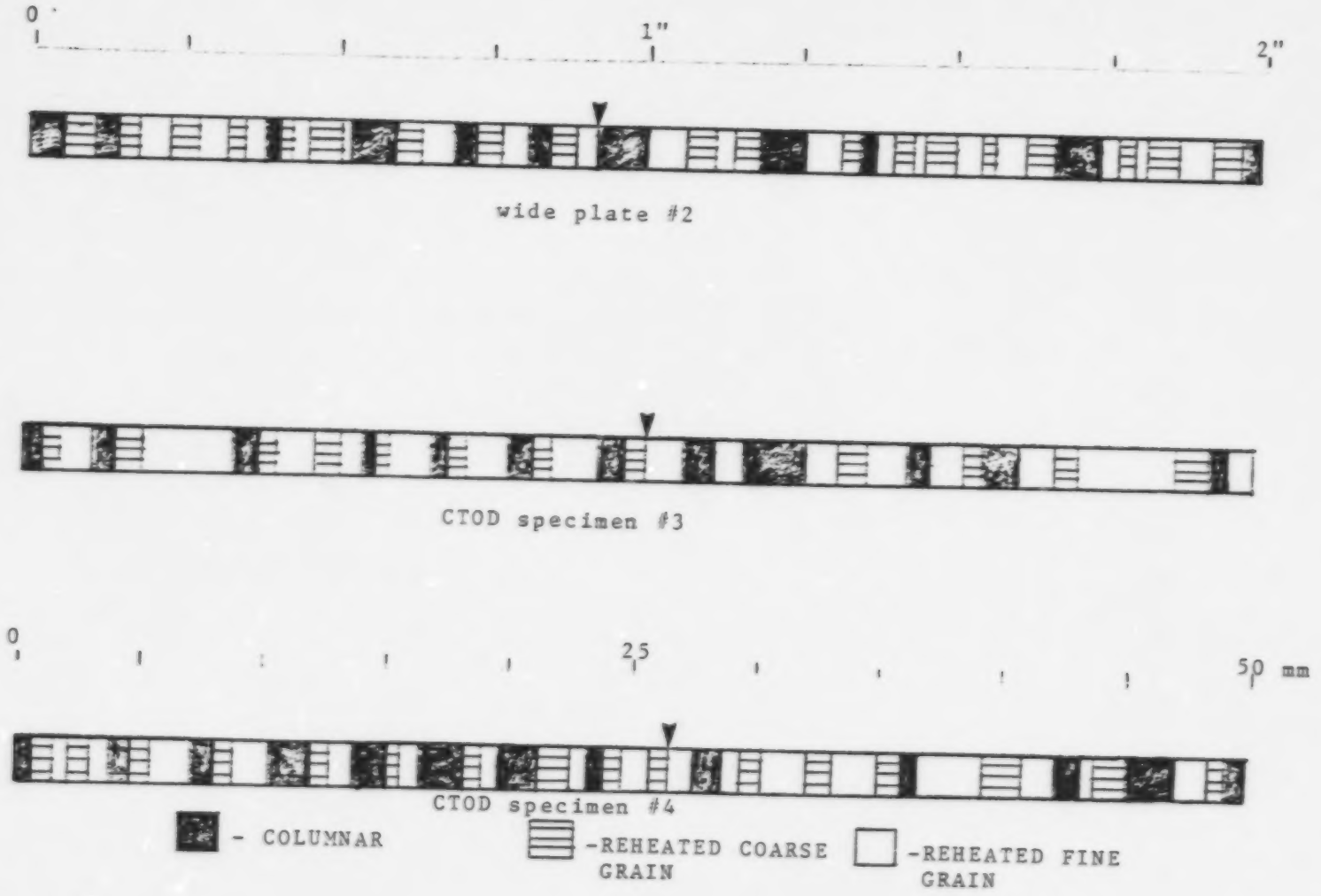


Figure 28. The weld metal microstructure sampled by the defect tips of 50 x 100mm CTOD specimens and wide plate #2. Arrow shows approximate fracture initiation site.

APPENDIX A

ALGOMA STEEL

The [redacted] Steel Corporation, Limited
Sault Ste. Marie, Ontario, Canada

CUSTOMER PURCHASE ORDER NUMBER	ENTRY DATE	SHIP DATE	SHIPPERS NUMBER	CARRIER	PAGE NO.	MILL ORDER
23378-3-6089	MAY 13/83	83-06-20	02 3524	S. GLEDHILL & SON (OUR 365	1 of 1	62124

CHARGE TO CUSTOMER NAME AND ADDRESS

ENERGY MINES & RESOURCES P.M.R.L.
568 BOOTH ST
OTTAWA ONTARIO
K1A 0G1

SHIP TO CUSTOMER NAME AND ADDRESS

ENERGY MINES & RESOURCES STOREKEEPER
556 BOOTH ST
CTTAWA ONTARIO
ATTN R THOMPSON

TEST REPORTS

WE HEREBY CERTIFY THAT THE MATERIAL HEREIN DESCRIBED WAS MADE AND TESTED IN ACCORDANCE WITH THE RULES OF THE SPECIFICATION SHOWN HEREIN AND AS CONTAINED IN THE CORPORATION RECORDS.

JUN 23 1983

SENIOR METALLURGIST

W.S.. PLATE MILL

CUSTOMER SPECIFICATION

HR PLATE - HSLA - LLOYDS LT.60 (1981) - CVNL 41 JOULES AT -60 C - ULTRASONIC TEST - 100% SCAN - TO ASTM A 578 1 - NORMALIZED - FLAME CUT

SUPPLEMENTARY INSTRUCTIONS

INSP T/R MILL SM/TR

CUST USE CONTACT D CEEKS

NN-NN-NN

HEAT AND INGOT NUMBER	IDENTIFICATION OF PIECE TESTED	WEIGHT	NUMBER OF PIECES	THICKNESS OF TEST	CONDITION OF TEST	TENSILE PROPERTIES YIELD MPA	TENSILE MPA	% ELONGATION 50	100	200	BEND	MC QUAID	IMPACT PROPERTIES TYPE DIRECT	1 JOUL	2 JOUL	3 JOUL	TEMP C
CUST ITEM	1 OUR ITEM 001	25.00 MM X 3048.00 MM X 1219 MM															
L1028	32345	9645	6	25	*NORM	403	513			31			CVNL	260	241	295	-60
L1028	32346	9645	6	25	*NORM	410	517			28			CVNL	177	80	162	-60
L1028	32347	6430	4	25	*NORM	403	510			27			CVNL	231	235	239	-60

L1028 C .12.MN 1.39.S .011.P .017.SI .28.CR .17.NI .15.CU .1S. AL .027.CB .041.V .053

*ULTRASONIC TEST TO ASTM A578

ALGOMA STEEL

The Algoma Steel Corporation, Limited
Sault Ste. Marie, Ontario, Canada

CUSTOMER PURCHASE ORDER NUMBER	ENTRY DATE	SHIP DATE	SHIPPERS NUMBER	CARRIER	PAGE NO.	MILL ORDER
23378-3-6089	MAY 13/83	83-06-17	02 3493	NICKEL CITY TRANSPORT (189	1 of 2	62124

CHARGE TO CUSTOMER NAME AND ADDRESS

ENERGY MINES & RESOURCES P.M.R.L.
568 BOOTH ST
OTTAWA ONTARIO
K1A 0G1

SHIP TO CUSTOMER NAME AND ADDRESS

ENERGY MINES & RESOURCES STOREKEEPER
556 BOOTH ST
OTTAWA ONTARIO
ATTN R THOMPSON

TEST REPORTS

WE HEREBY CERTIFY THAT THE MATERIAL HEREIN DESCRIBED WAS MADE AND TESTED IN ACCORDANCE WITH THE RULES OF THE SPECIFICATION SHOWN HEREIN AND AS CONTAINED IN THE CORPORATION RECORDS.

AUG 18 1983

D. Casagrande
SENIOR METALLURGIST

W.S.. PLATE MILL

CUSTOMER SPECIFICATION

HR PLATE - HSLA - LLOYDS LT.60 (1981) - CVNL 41 JOULES AT -60 C - ULTRASONIC TEST - 100% SCAN - TO ASTM A 578 1 - NORMALIZED - FLAME CUT

SUPPLEMENTARY INSTRUCTIONS

Jim Ley

INSP T/R MILL SM/TR

CUST USE CONTACT D DEEKS

NN-NN-NN

HEAT AND INGOT NUMBER	IDENTIFICATION OF PIECE TESTED	WEIGHT	NUMBER OF PIECES	THICKNESS OF TEST	CONDITION OF TEST	TENSILE PROPERTIES YIELD MPA	TENSILE MPA	% ELONGATION 50	100	200	BEND	MC QUAID	IMPACT PROPERTIES TYPE DIRECT	1 JOUL	2 JOUL	3 JOUL	TEMP °C
CUST ITEM 2 OUR ITEM 002 50.00 MM X 2438.40 MM X 1524 MM																	
L1028	32336	9647	3	50.80	*Norm	391	520	30					-80 CVNL	102	139	135	-76C
L1028	32337	9647	3	50.80	*Norm	403	520	30					CVNL	270	322	201	-6C
L1028	32339	6431	2	50.80	*Norm	395	522	32					CVNL	196	178	276	-6C
L1028	32340	6431	2	50.80	*Norm	386	513	36					CVNL	202	163	137	-6C
L1028	32341	9647	3	50.80	*Norm	388	517	32					CVNL	160	184	193	-6C
L1028	32342	9647	3	50.80	*Norm	379	510	31					RT CVNL	340	335	233	-60
CUST ITEM 4 OUR ITEM 003 75.00 MM X 2438.40 MM X 1524 MM																	

* ULTRASONIC TESTED TO ASTM A 578

CONTINUED ON NEXT PAGE

WELDING DATA SHEET

WELDING INSTITUTE OF CANADA
INSTITUT DE SOUDAGE DU CANADA

CONTRACT NO. RC 307

DATA SHEET NO. ~~GTOD WELD (25mm~~ THICK PLATE)

PROCESS: SMAW

MATERIALS: G 40 21 Gr. 350 WT

POSITION: 3G - Vertical UP

PREHEAT:

Preheat Temp. 38°C
Interpass Temp. 120°C
Preheat Maintenance

FILLER METAL:

Classification E48018-1
Trade Name CLA LA-18 PLUS

FLUX:

Class:
Trade Name:

GAS COMPOSITION REQUIRED:

Shielding Gas	At	CFH
Backing Gas	At	CFH
Trailing Gas	At	CFH

ELECTRICAL CHARACTERISTICS:

Power Source:
Current Type: DC
Polarity +VE

SPECIAL NOTES

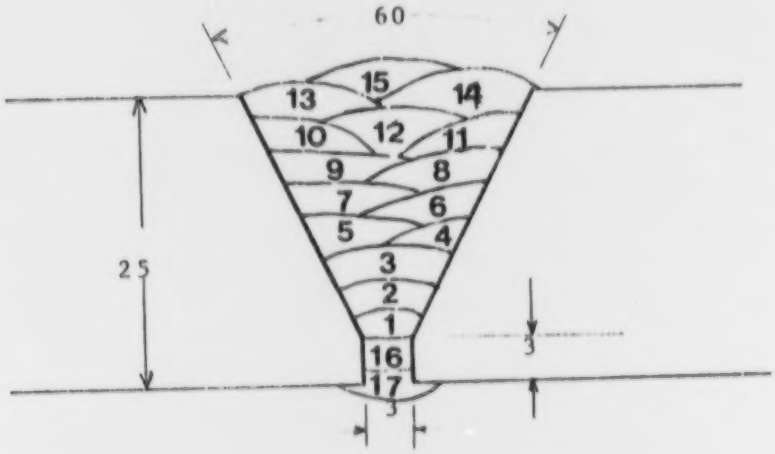
T	WELD SEQUENCE			ELECTRODE		WELDING VARIABLES					
	SIDE	LAYER	PASS	TYPE	SIZE mm	AMPS	VOLTS	E.S.O.	SPEED mmps	WFS ipm	HEAT INPUT
	1		1-15	48018-1	3.2	115-127			1.4		2 kJ/mm
	2		16-17	"	"	"			"		"

ISSUED BY:

DATE:

LAB TECHNOLOGIST:

ADDITIONAL NOTES:



BACK-GOUGED

T	WELD SEQUENCE			ELECTRODE		WELDING VARIABLES					
	SIDE	LAYER	PASS	TYPE	SIZE mm	AMPS	VOLTS	E.S.O.	SPEED mmps	WFS ipm	HEAT INPUT

WELDING DATA SHEET

WELDING INSTITUTE OF CANADA
INSTITUT DE SOUDAGE DU CANADA

CONTRACT NO. RC 307

DATA SHEET NO. WIDE PLATE #1 (CLA 1A)

PROCESS: SMAW

MATERIALS: G 40.21 GR. 350 WT

POSITION: 3G - VERTICAL UP

PREHEAT:

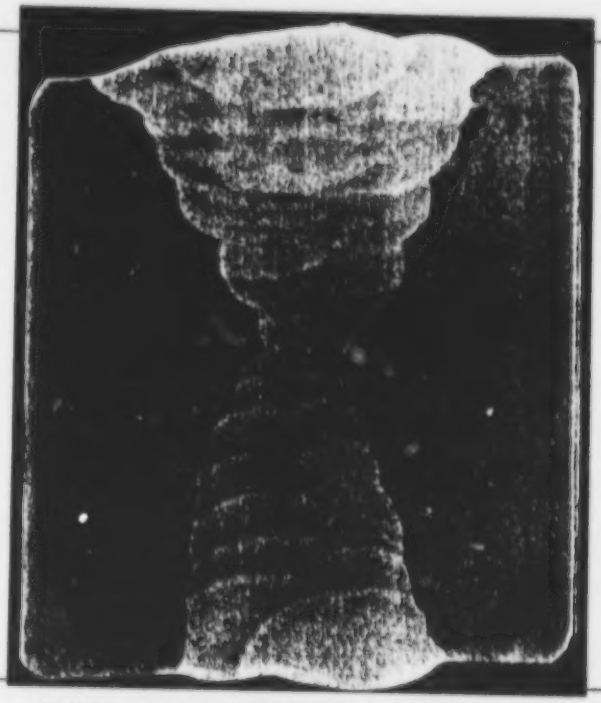
Preheat Temp. 38°C
Interpass Temp. 150°C Max.
Preheat Maintenance

FILLER METAL:

Classification E48018-1
Trade Name CLA 1A-18 PLUS
(LOT NO. 215130J7)

FLUX:

Class:
Trade Name:



GAS COMPOSITION REQUIRED:

Shielding Gas	At	CFH
Backing Gas	At	CFH
Trailing Gas	At	CFH

ELECTRICAL CHARACTERISTICS:

Power Source:
Current Type: DC
Polarity: +VE

SPECIAL NOTES

T	WELD SEQUENCE			ELECTRODE		WELDING VARIABLES					
	SIDE	LAYER	PASS	TYPE	SIZE mm	AMPS	VOLTS	E.S.O.	SPEED mmps	WFS ipm	HEAT INPUT
	1		1-17	48018-1	3.2	120-130	24		1.4-1.5		2kJ/mm
	2		18-39	"	"	"	"		"		

ISSUED BY:

DATE:

LAB TECHNOLOGIST:

WELDING DATA SHEET

WELDING INSTITUTE OF CANADA
INSTITUT DE SOUDAGE DU CANADA

CONTRACT NO. RC 307

DATA SHEET NO. WIDE PLATE #2 (CLA2A)

PROCESS: SMAW

MATERIALS: G 40.21 GR 350WT

POSITION: 3G - Vertical UP

PREHEAT:

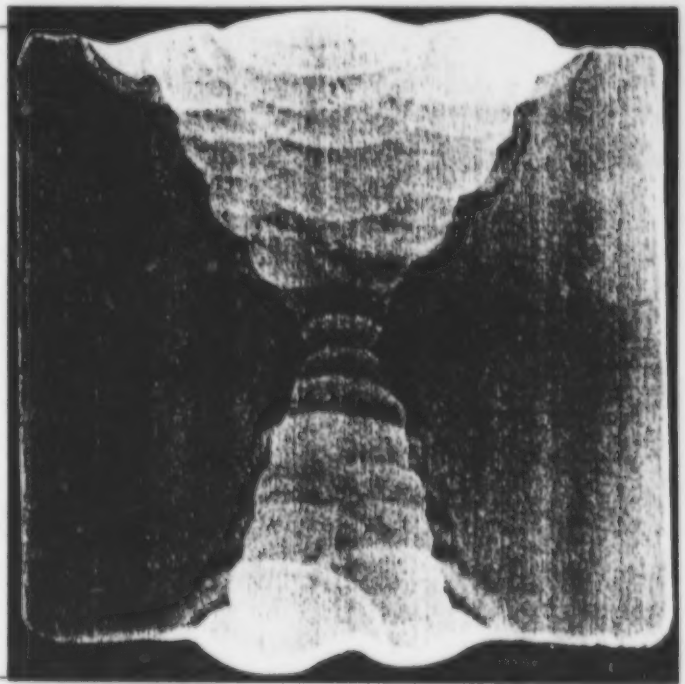
Preheat Temp. 38°C
Interpass Temp. 150°C
Preheat Maintenance

FILLER METAL:

Classification E48018-1
Trade Name CLA LA-18 Plus
(Lot No. 21463037)

FLUX:

Class:
Trade Name:



GAS COMPOSITION REQUIRED:

Shielding Gas	At		CFH
Backing Gas	At		CFH
Trailing Gas	At		CFH

ELECTRICAL CHARACTERISTICS:

Power Source:
Current Type: DC
Polarity: +VE

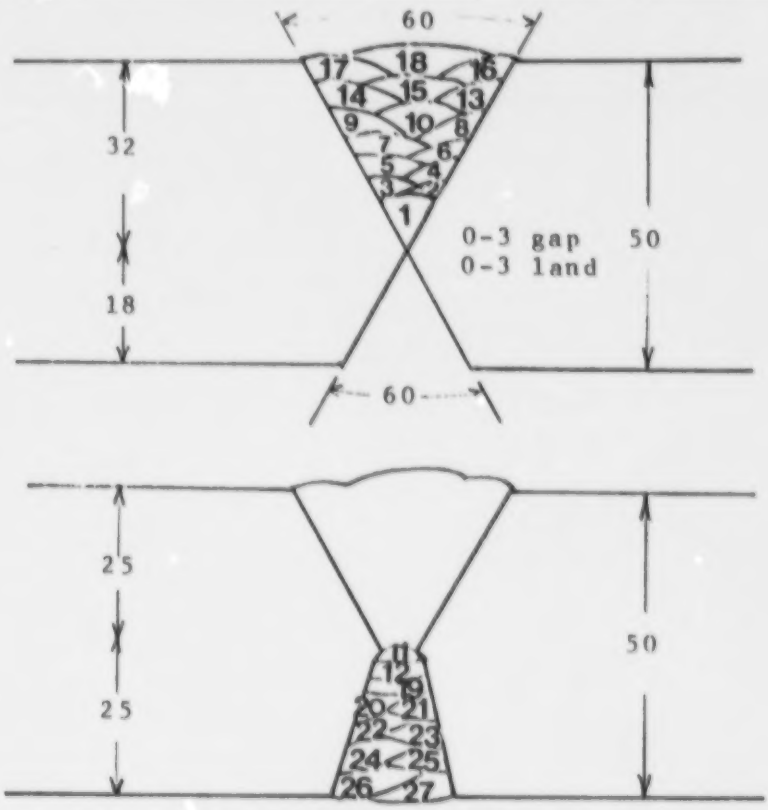
SPECIAL NOTES

T	WELD SEQUENCE			ELECTRODE		WELDING VARIABLES					
	SIDE	LAYER	PASS	TYPE	SIZE mm	AMPS	VOLTS	E.S.O.	SPEED mmps	WFS ipm	HEAT INPUT
	1		1-10	48018-1	3.2	125-135	24		1.5-1.7		2kJ/mm
	2		11-12	"	"	"	"		"		"
	1		13-18	"	"	"	"		"		"
	2		19-27	"	"	"	"		"		"

ISSUED BY: DATE: LAB TECHNOLOGIST:

ADDITIONAL NOTES:

Wide plate #2



BACK-GOUGED

T	WELD SEQUENCE			ELECTRODE		WELDING VARIABLES					
	SIDE	LAYER	PASS	TYPE	SIZE mm	AMPS	VOLTS	E.S.O.	SPEED mmps	WFS ipm	HEAT INPUT

WELDING DATA SHEET

WELDING INSTITUTE OF CANADA
INSTITUT DE SOUDAGE DU CANADA

CONTRACT NO. RC 307

DATA SHEET NO. Wide Plate #3 (CLA 3A)

PROCESS: SMAW

MATERIALS: G4021 GR 350WT

POSITION: 3G - Vertical UP

PREHEAT:

Preheat Temp. 38°C
Interpass Temp. 150°C
Preheat Maintenance

FILLER METAL:

Classification E48018-1
Trade Name CLA LA - 18 Plus
(Lot No. 21463UJ7)

FLUX:

Class:
Trade Name:

GAS COMPOSITION REQUIRED:

Shielding Gas	At	CFH	
Backing Gas	At	CFH	
Trailing Gas	At	CFH	

ELECTRICAL CHARACTERISTICS:

Power Source:
Current Type: DC
Polarity: +VE

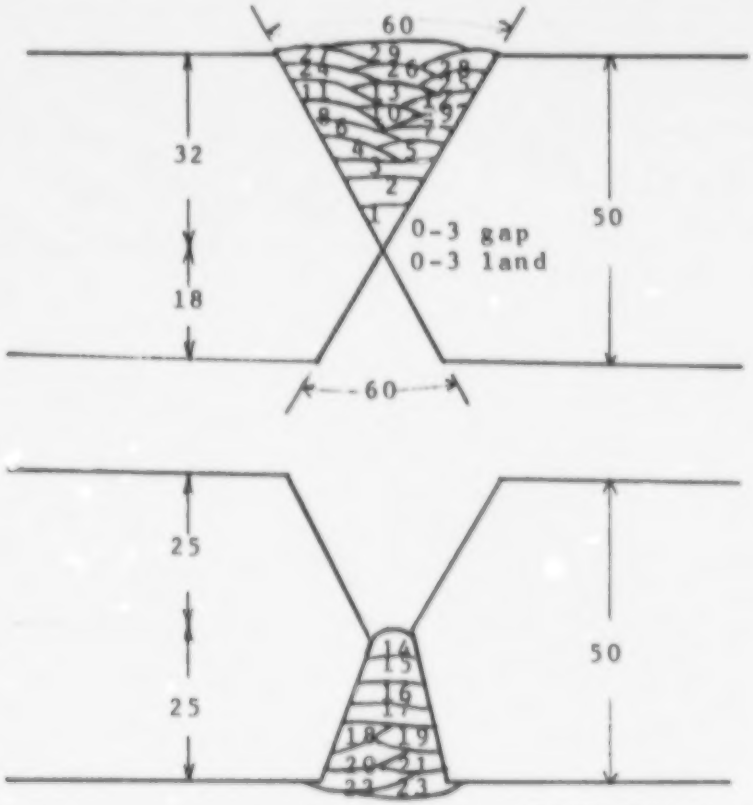
SPECIAL NOTES

T	WELD SEQUENCE			ELECTRODE		WELDING VARIABLES					
	SIDE	LAYER	PASS	TYPE	SIZE mm	AMPS	VOLTS	E.S.O.	SPEED mmps	WFS ipm	HEAT INPUT
	1		1-13	48018-1	3.2	135	24		1.5		2kJ/mm
	2		14-23	"	"	"	"		"		"
	1		24-29	"	"	"	"		"		"

ISSUED BY: DATE: LAB TECHNOLOGIST:

ADDITIONAL NOTES:

Wide plate #3



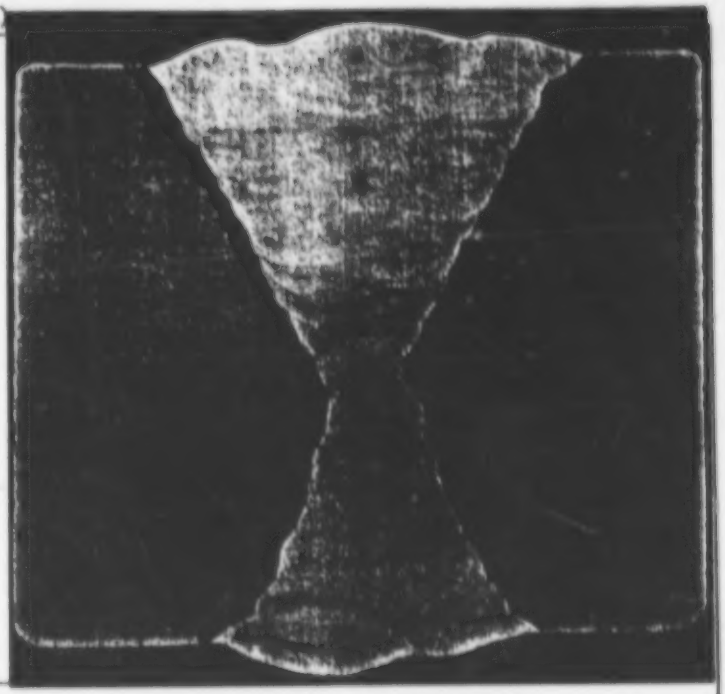
T	WELD SEQUENCE			ELECTRODE		WELDING VARIABLES					
	SIDE	LAYER	PASS	TYPE	SIZE mm	AMPS	VOLTS	E.S.O.	SPEED mmps	WFS ipm	HEAT INPUT

WELDING DATA SHEET

WELDING INSTITUTE OF CANADA
INSTITUT DE SOUDAGE DU CANADA

CONTRACT NO. RG 107

DATA SHEET NO. Wide Plate #4 (CLA 4 A)



PROCESS: SMAW

MATERIALS: G40 21 GR 350 WT

POSITION: 3G - Vertical UP

PREHEAT:

Preheat Temp. 38°C
Interpass Temp. 150°C
Preheat Maintenance

FILLER METAL:

Classification E48018-1
Trade Name CLA LA-18 Plus
(Lot No. 52021518)

FLUX:

Class:
Trade Name:

GAS COMPOSITION REQUIRED:

Shielding Gas	At	CFH
Backing Gas	At	CFH
Trailing Gas	At	CFH

ELECTRICAL CHARACTERISTICS:

Power Source:
Current Type: DC
Polarity: +VE

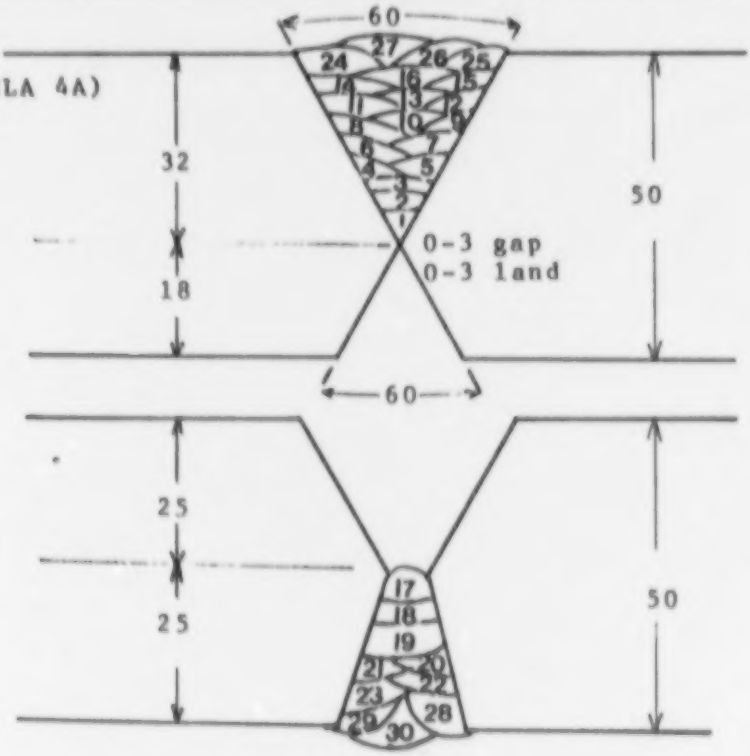
SPECIAL NOTES

T	WELD SEQUENCE			ELECTRODE		WELDING VARIABLES					
	SIDE	LAYER	PASS	TYPE	SIZE mm	AMPS	VOLTS	E.S.O.	SPEED mmps	WFS lpm	HEAT INPUT
	1		1-16	48018-1	3.2	130	24		1.4-1.5		2 kJ/mm
	2		17-23	"	"	"	"		"		"
	3		24-27	"	"	"	"		"		"
	4		29-30	"	"	"	"		"		"

ISSUED BY: | DATE: | LAB TECHNOLOGIST:

ADDITIONAL NOTES:

Wide plate #4 (CLA 4A)



BACKGOUGED

T	WELD SEQUENCE			ELECTRODE		WELDING VARIABLES					
	SIDE	LAYER	PASS	TYPE	SIZE mm	AMPS	VOLTS	E.S.O.	SPEED mmps	WFS ipm	HEAT INPUT

WELDING DATA SHEET

WELDING INSTITUTE OF CANADA
INSTITUT DE SOUDAGE DU CANADA

CONTRACT NO. RL: 307

DATA SHEET NO. CTOD WIDE PLATE (CLASA)

PROCESS: SMAW

MATERIALS: G40·21 GR 350 WT

POSITION: 3G - Vertical UP

PREHEAT:

Preheat Temp. 38°C
Interpass Temp. 150°C
Preheat Maintenance

FILLER METAL:

Classification E48U18-1
Trade Name CLA LA-18 Plus
(Lot No. 52021518)

FLUX:

Class:
Trade Name:

JOINT DETAILS

GAS COMPOSITION REQUIRED:

Shielding Gas	At	CFH
Backing Gas	At	CFH
Trailing Gas	At	CFH

ELECTRICAL CHARACTERISTICS:

Power Source:
Current Type: DC
Polarity: +VE

SPECIAL NOTES

T	WELD SEQUENCE			ELECTRODE		WELDING VARIABLES					
	SIDE	LAYER	PASS	TYPE	SIZE mm	AMPS	VOLTS	E.S.O.	SPEED mmps	WFS ipm	HEAT INPUT
	1		1-21	48018-1	3.2	125	24		1.5		2 kJ/mm
	2		22-31	"	"	"	"		"		"

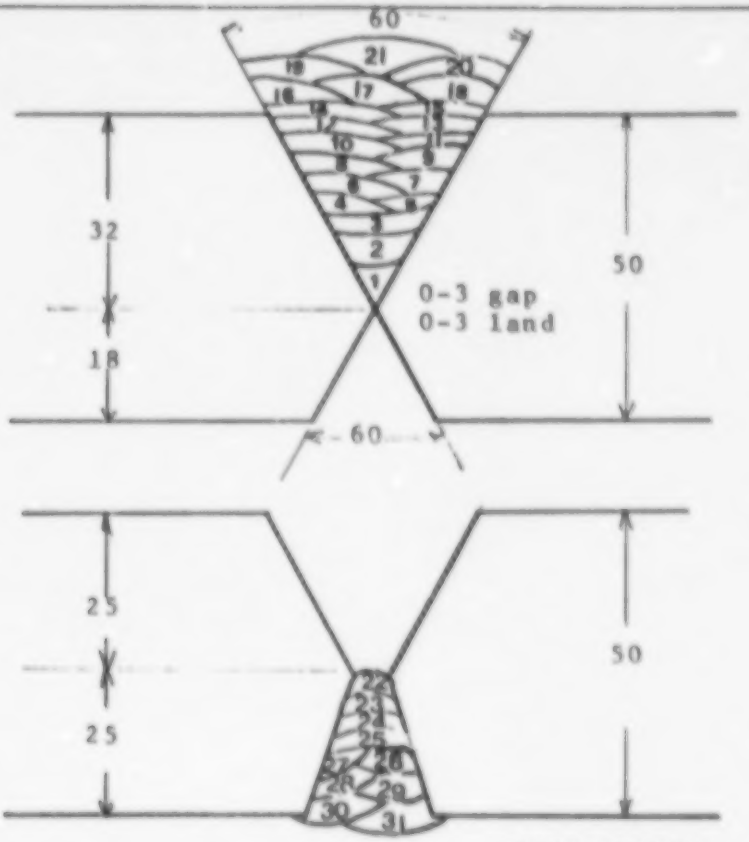
ISSUED BY:

DATE:

LAB TECHNOLOGIST:

ADDITIONAL NOTES:

CLA plate #5A



T	WELD SEQUENCE			ELECTRODE		WELDING VARIABLES					
	SIDE	LAYER	PASS	TYPE	SIZE mm	AMPS	VOLTS	E.S.O.	SPEED mmps	WFS ipm	HEAT INPUT

WELDING DATA SHEET

WELDING INSTITUTE OF CANADA
INSTITUT DE SOUDAGE DU CANADA

CONTRACT NO. RC507

DATA SHEET NO. Wide Plate #5 (CLA 6A)

PROCESS: SMAW

MATERIALS: G40 21 GR 350WT

POSITION: 3G - Vertical UP

PREHEAT:

Preheat Temp. 38°C
Interpass Temp. 150°C Max
Preheat Maintenance

FILLER METAL:

Classification E48018-1
Trade Name CLA LA-18 Plus
(Lot No. 52021518)

FLUX:

Class:
Trade Name:

GAS COMPOSITION REQUIRED:

Shielding Gas	At	CFH
Backing Gas	At	CFH
Trailing Gas	At	CFH

ELECTRICAL CHARACTERISTICS:

Power Source:
Current Type: DC
Polarity: +VE

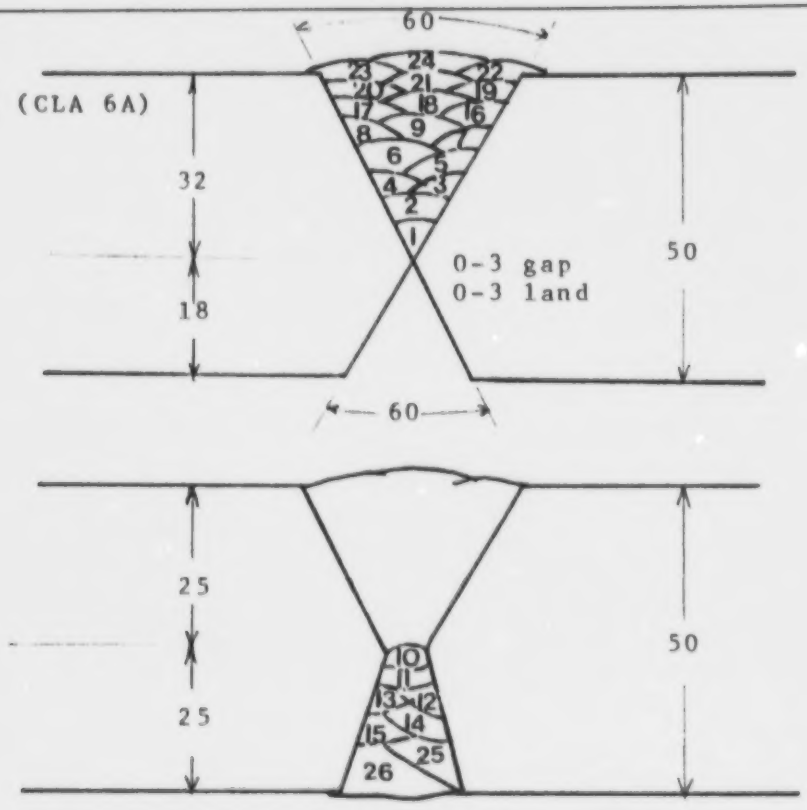
SPECIAL NOTES

T	WELD SEQUENCE			ELECTRODE		WELDING VARIABLES					
	SIDE	LAYER	PASS	TYPE	SIZE mm	AMPS	VOLTS	E.S.O.	SPEED mmps	WFS ipm	HEAT INPUT
	1		1-9	48018-1	3.2	130	24		1.4-1.6		2 kJ/mm
	2		10-15	"	"	"	"		"		"
	1		16-24	"	"	"	"		"		"
	2		25-26	"	"	"	"		"		"

ISSUED BY:	DATE:	LAB TECHNOLOGIST:

ADDITIONAL NOTES:

Wide plate #5 (CLA 6A)



BACK-GOUGED

T	WELD SEQUENCE			ELECTRODE		WELDING VARIABLES					
	SIDE	LAYER	PASS	TYPE	SIZE mm	AMPS	VOLTS	E.S.O.	SPEED mmps	WFS ipm	HEAT INPUT

APPENDIX B

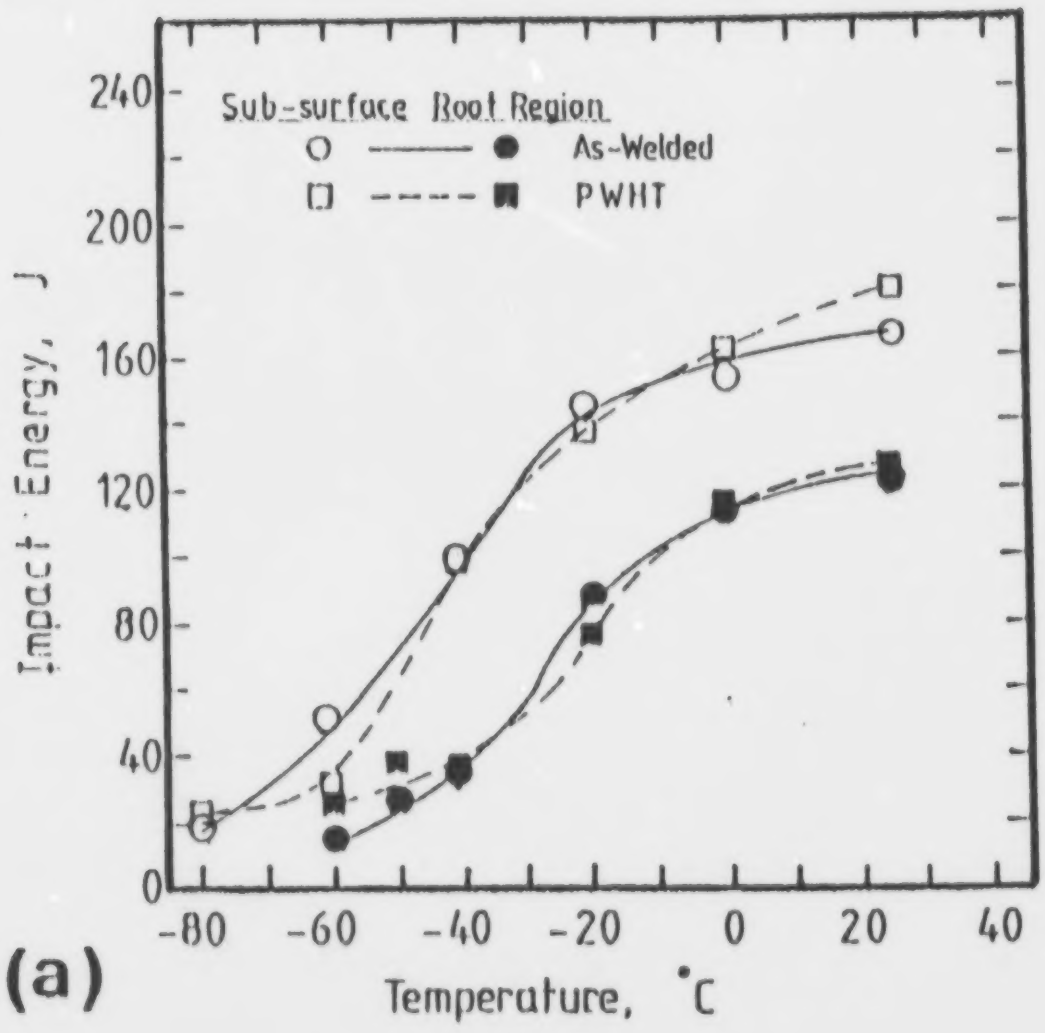


Figure B1. CVN transition curve for SMAW metal deposited from CLA LA 18 Plus (E48018-1) electrode (Ref. 4).

TABLE B1. Tensile Properties of SMAW Metal Deposited from CLA LA 18 - Plus Electrodes (Ref. 4).

Weld	Y.S. MPa	U.T.S. MPa	Elong. %	R.A. %
as-welded	541	613	24	68
stress-relieved	489	589	25	70

TABLE B2. CTOD Values of SMAW Metal Deposited from CLA LA 18 - Plus Electrodes (Ref. 4).

Weld	CTOD Values, mm	
	-30 deg. C	-10 deg. C
as-welded	0.17	0.12
	0.08	0.27
	0.16	0.25
stress-relieved	0.43	
	0.42	0.68
	0.15	

APPENDIX C

TABLE C1. Thermocouple Readings for Wide Plate Test #1.

Pressure psi	Temperature deg. C									
	TW1	TW2	TW3	TW4	TE5	TE6	TE7	TE8	INLET	OUTLET
0	0	-31	-28	-29	2	-30	-31	-30	-43	-30
1000	0	-31	-28	-29	1	-30	-31	-30	-44	-31
5000	0	-31	-28	-29	1	-30	-31	-31	-44	-31
8000	0	-32	-28	-30	1	-30	-32	-32	-45	-31
10000	0	-32	-29	-30	1	-30	-32	-31	-43	-30
12000	0	-30	-29	-29	1	-29	-30	-30	-41	-29
13300	0	-30	-29	-29	1	-30	-31	-31	-44	-30
0	0	-30	-29	-29	1	-30	-31	-31	-44	-30

TABLE C2. Thermocouple Readings for Wide Plate Test #2.

Pressure psi	Temperature deg. C							
	TW1	TW2	TW3	TE5	TE6	TE8	INLET	OUTLET
0	1	-54	-54	-5	-55	-53	-75	-88
500	1	-54	-55	-5	-53	-53	-86	-100
4000	1	-51	-50	-5	-50	-54	-90	-105
6000	1	-53	-52	-4	-52	-55	-94	-110
8500	1	-51	-53	-4	-54	-54	-94	-110
0	1	-52	-52	-4	-54	-54	-60	-100

TABLE C3. Thermocouple Readings for Wide Plate Test #3.

Pressure psi	Temperature deg. C									
	TW3	TW4	TW5	TW6	TE5	TE6	TE7	TE9	INLET	OUTLET
0	-47	-54	-49	-47	-4	-56	-53	-49	-62	-73
5000	-48	-55	-51	-48	-4	-49	-55	-50	-68	-81
7000	-50	-53	-50	-50	-5	-50	-54	-51	-72	-90
9000	-50	-53	-53	-50	-5	-52	-53	-52	-74	-93
11000	-50	-50	-54	-51	-5	-50	-53	-52	-76	-96
13000	-51	-51	-55	-52	-5	-54	-52	-54	-77	-97
13750	-52	-52	-54	-53	-5	-55	-50	-55	-77	-99
13950	-53	-54	-56	-58	-5	-55	-52	-54	-77	-98
										-97

TABLE C4. Thermocouple Readings for Wide Plate Test #4.

Pressure psi	Temperature deg.C										
	TW1	TW3	TW4	TW5	TW6	TE5	TE6	TE9	TE10	INLET	OUTLET
0	8	-55	-55	-52	-55	3	-47	-52	-54	-71	-98
500	7	-55	-54	-52	-56	4	-48	-53	-55	-71	-98
2000	6	-54	-54	-52	-55	3	-48	-53	-55	-66	-99
4000	6	-54	-53	-52	-55	4	-48	-52	-55	-65	-93
8000	6	-49	-53	-48	-48	2	-48	-54	-49	-64	-95
10500	5	-49	-52	-49	-48	1	-48	-54	-47	-56	-85
13500	4	-51	-50	-51	-52	1	-47	-50	-49	-58	-88
14500	4	-51	-50	-53	-54	0	-48	-53	-54	-60	-90
16000	4	-51	-51	-53	-54	-1	-48	-55	-54	-66	-99

TABLE C5. Thermocouple Readings for Wide Plate Test #5.

Pressure psi	Temperature deg. C										
	TW3	TW4	TW5	TW7	TE5	TE6	TE7	TE11	TE12	INLET	OUTLET
0	-55	-54	-55	-55	-11	-49	-55	-55	-56	-75	-98
1000	-55	-53	-50	-55	-11	-48	-55	-53	-55	-76	-94
3000	-54	-48	-45	-48	-11	-46	-47	-47	-53	-70	-90
8000	-51	-50	-48	-53	-11	-45	-55	-51	-47	-60	-60
10000	-54	-53	-50	-55	-11	-46	-55	-53	-51	-68	-87
12000	-53	-55	-52	-55	-11	-45	-55	-54	-54	-67	-90
14000	-55	-55	-53	-55	-11	-46	-55	-54	-55	-66	-90
14500	-55	-53	-53	-55	-11	-46	-55	-53	-55	-66	-90

APPENDIX D

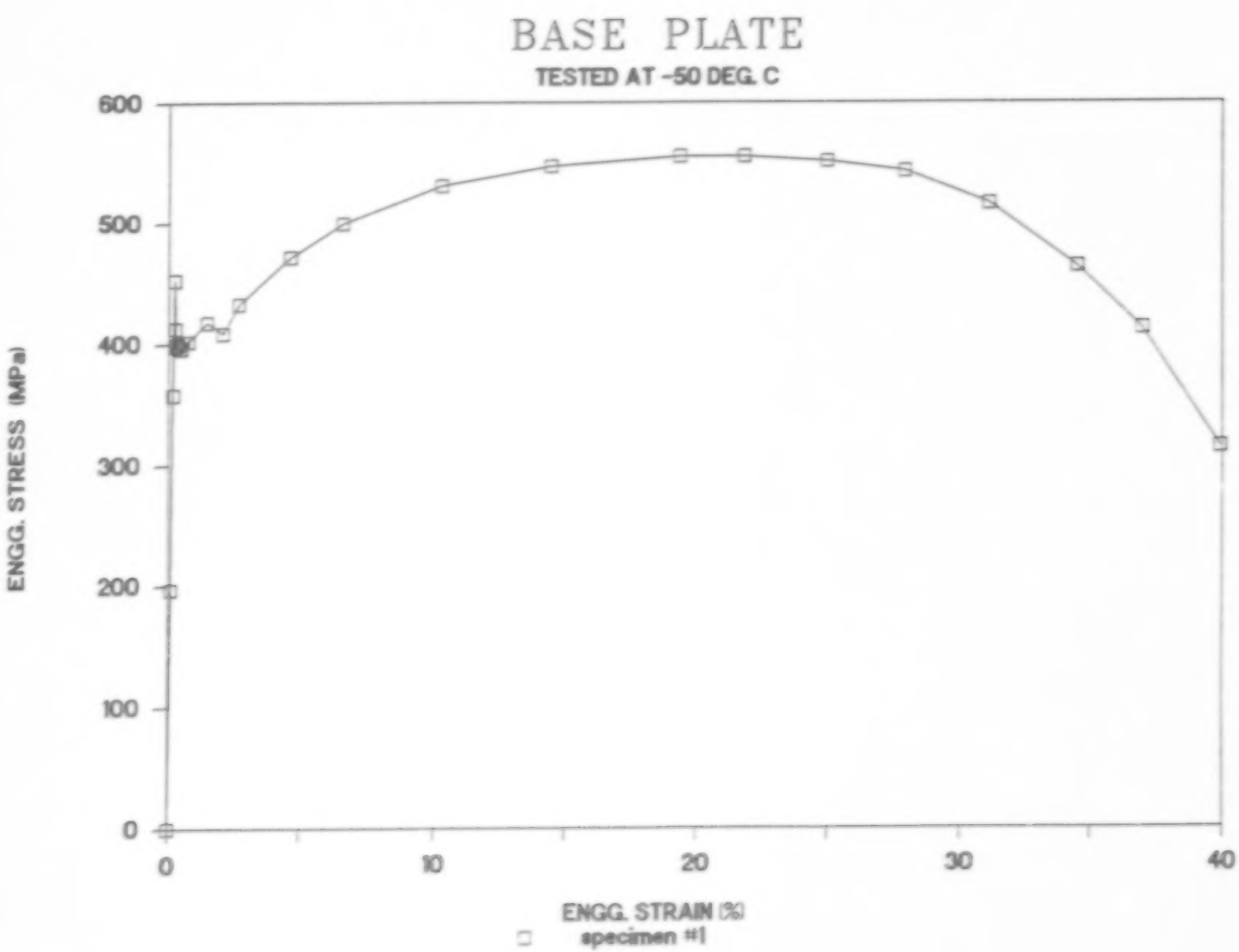


Figure D1. Engineering stress-strain curve for the base plate, specimen #1.

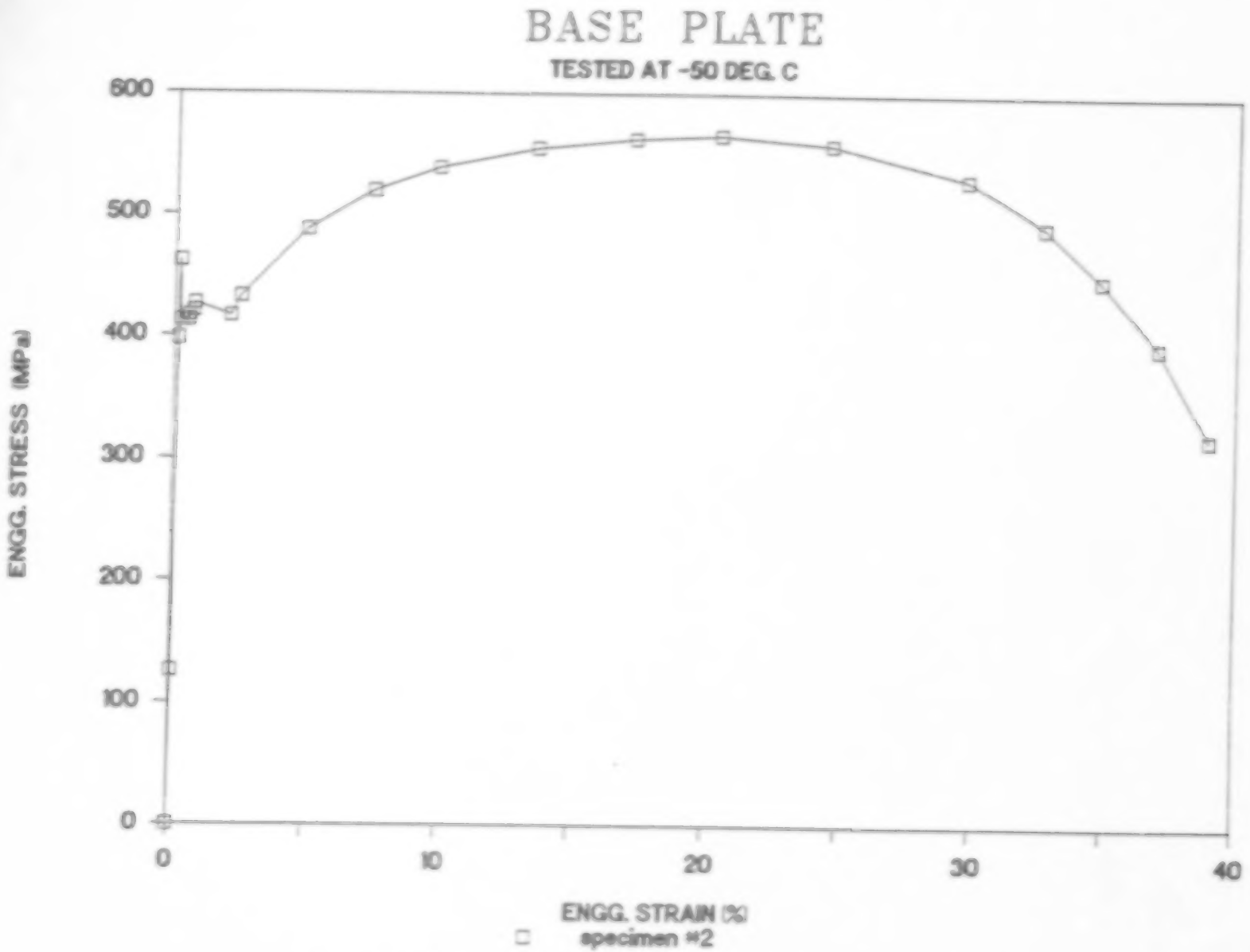


Figure D2. Engineering stress-strain curve for the base plate, specimen #2.

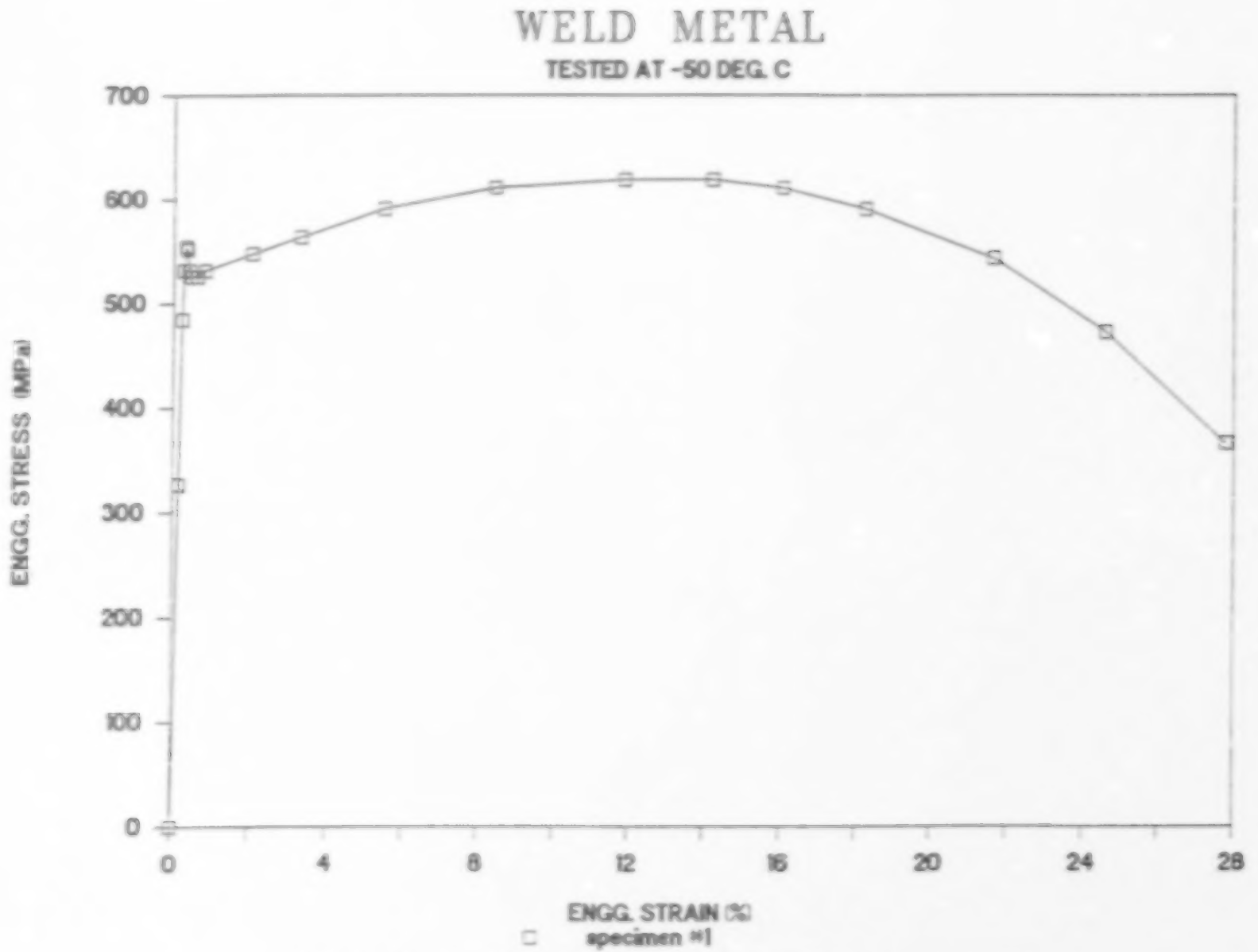


Figure D3. Engineering stress-strain curve for the weld metal, specimen #1.

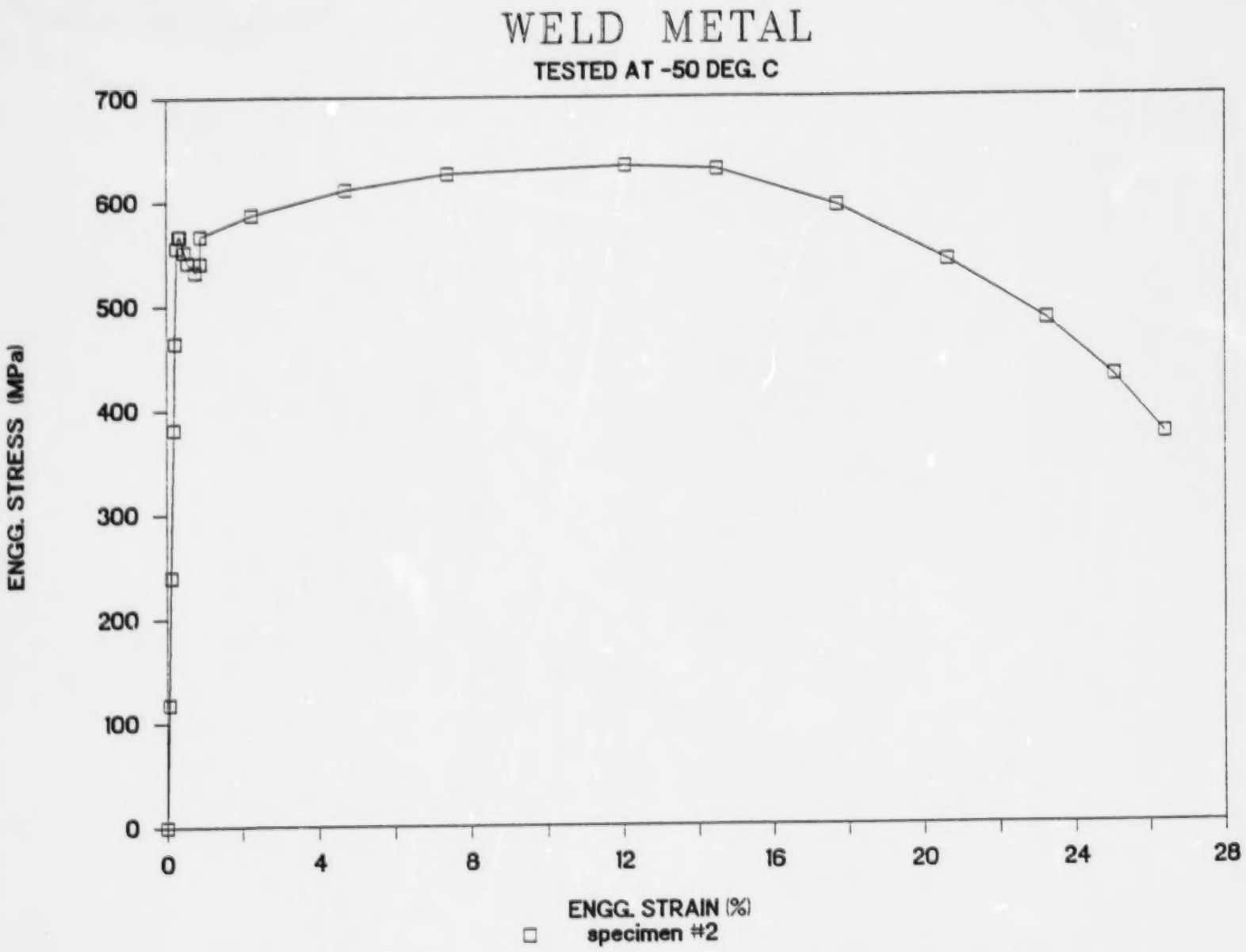


Figure D4. Engineering stress-strain curve for the weld metal, specimen #2.

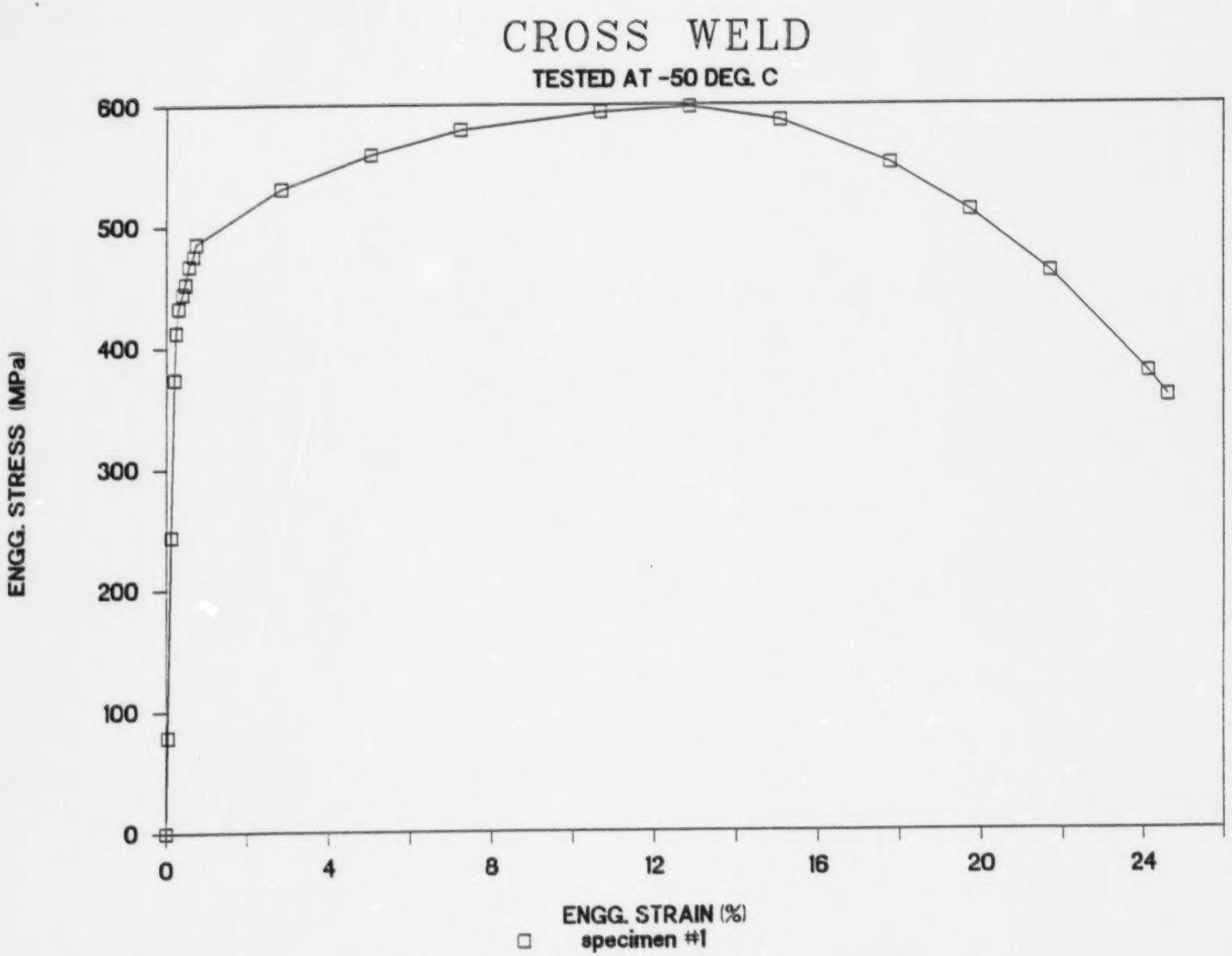


Figure D5. Engineering stress-strain curve for the cross weld, specimen #1.

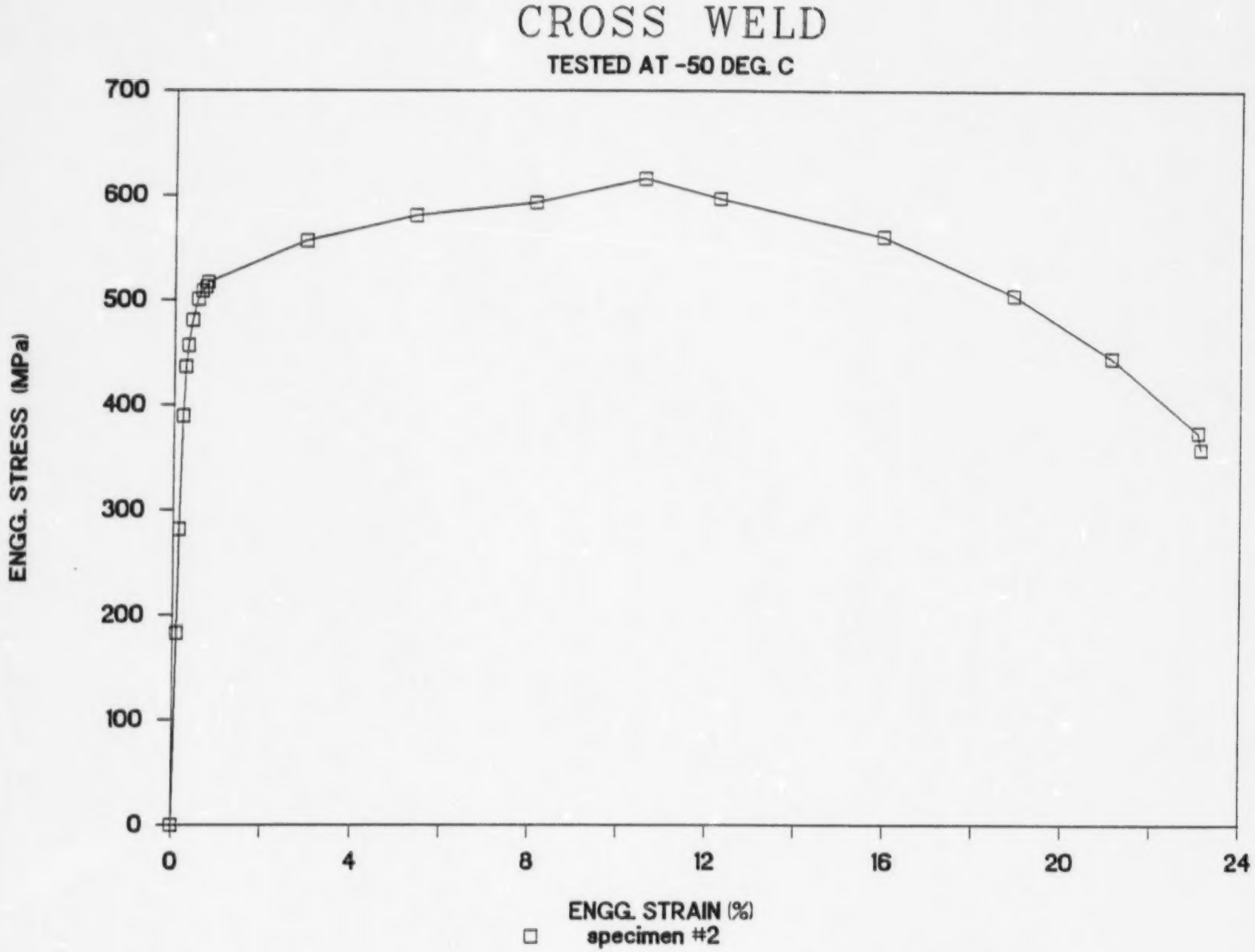


Figure D6. Engineering stress-strain curve for the cross weld, specimen #2.

TABLE D1.

TENSILE TEST REPORT

Client:

Client P.O. Number:

WIC Contract Number: RC 307

Test Standard: E-8

Specimen Standard:

Specimen Type:

Specimen Material:

Specimens Machined By:

Specimen Number	Plate	Plate		Weld	Weld
Initial Thickness or Diameter (mm)	12.72	12.72		12.71	12.71
Initial Width (mm)					
Initial Cross-sectional Area (mm^2)	127	127		127	127
Initial Gauge Length (mm)	50	50		50	50
Final Thickness or Diameter (mm)					
Final Width (mm)					
Final Cross-sectional Area (mm^2)					
Final Gauge Length (mm)	71.12	71.12		65.53	65.28
Yield or Offset Load* (kN) Upper Lower	57.50 50.00	58.49 52.50		70.50 66.75	72.00 67.50
Maximum Load (kN)	70.50	71.75		78.50	80.50
Yield Stress (MPa) Upper Lower	452 394	461 413		556 526	567 532
Ultimate Tensile Strength (MPa)	555	565		619	634
Elongation (%)	40	40		29	28.5
Reduction of Area (%)					
Failure Location					

* Percentage of offset used to determine offset load: 0.1, 0.2, 0.5

Comments

Date:

Tested by:

Witnessed by:

Project Engineer:

TABLE D2

TENSILE TEST REPORT

Client:

Client P.O. Number:

WIC Contract Number: RC 307

Test Standard: E-8

Specimen Standard:

Specimen Type:

Specimen Material:

Specimens Machined By:

Specimen Number	Cross Weld				
Initial Thickness or Diameter (mm)	12.72	12.65			
Initial Width (mm)					
Initial Cross-sectional Area (mm^2)	127	126			
Initial Gauge Length (mm)	50	50			
Final Thickness or Diameter (mm)					
Final Width (mm)					
Final Cross-sectional Area (mm^2)					
Final Gauge Length (mm)	64.26	63.75			
Yield or Offset Load* (kN) 0.2% 0.5%	56.50 62.00	61.00 65.00			
Maximum Load (kN)	75.75	75.50			
Yield Stress (MPa) 0.2% 0.5%	448 488	485 517			
Ultimate Tensile Strength (MPa)	596	601			
Elongation (%)	26.5	25.5			
Reduction of Area (%)					
Failure Location					

* Percentage of offset used to determine offset load: 0.1, 0.2, 0.5

Comments

Date:

Tested by:

Witnessed by:

Project Engineer:

[redacted] TO[redacted]RAC[redacted]E T[redacted]UN[redacted]TE[redacted]LAB[redacted]ORY [redacted]PO[redacted]

TABLE D3

Cont. [redacted]t No:

Spec No.	Temp (°C)	a_{25} (mm)	a_{50} (mm)	a_{75} (mm)	a_{min} (mm)	a_{max} (mm)	a_{avg} (mm)	B (mm)	W (mm)	Y	σ_y (MPa)	V_p (mm)	P_{max} (KN)	ELASTIC (mm)	PLASTIC (mm)	δ (mm)
1	-50	25.94	26.13	25.31			25.80	25.48	51.82	10.53	529	0.2845	62.50	0.0533	0.0762	0.130
2	-50	25.53	25.72	24.49			25.25	25.48	51.82	10.19	529	0.4902	68.99	0.0610	0.1372	0.198
3	-50	25.69	26.21	25.62			25.84	25.20	51.82	10.56	529	0.1168	53.00	0.0381	0.0305	0.069
4	-50	25.67	27.03	26.68			26.46	25.22	51.82	10.99	529	0.0965	50.00	0.0381	0.0254	0.064
5	-50	25.44	25.66	25.86			25.65	25.22	51.82	10.45	529	0.2108	60.74	0.0508	0.0584	0.109
6	-50	24.28	23.07	23.54			23.63	25.65	50	9.52	529	0.1245	60.00	0.0406	0.0356	0.076
7	-50	25.42	25.72	25.18			25.44	26.01	50	10.65	529	0.1676	57.50	0.0457	0.0457	0.091
8	-50	24.35	24.38	24.98			24.57	25.60	50	10.07	529	0.053	45.25	0.0254	0.0152	0.041*
9	-50	24.56	23.53	25.06			24.38	25.65	50	9.96	529	0.1880	61.00	0.0457	0.0533	0.100
10	-50			23.62			24.18	26.06	50	9.84	529	0.6883	67.00	0.0533	0.1981	0.25

Comments:

25 x 50mm CTOD SPECIMENS

FATIGUE PRECRACK

* - δ_c values,
All others are δ_u values

Date:
Tested By:
Witnessed By:
Project Engineer:

CTOD FRACTURE TOUGHNESS TEST LABRATORY REPORT

TABLE D4

Cont[illegible]t No:

Spec No.	Temp (°C)	a_{25} (mm)	a_{50} (mm)	a_{75} (mm)	a_{min} (mm)	a_{max} (mm)	a_{avg} (mm)	B (mm)	W (mm)	Y	σy (MPa)	V_p (mm)	P_{max} (kN)	ELASTIC (mm)	PLASTIC (mm)	δ (mm)
1	-30	25.04	25.07	25.11			25.07	25.78	50.00	10.39	529	2.5984		0.0686	0.7087	> 0.780
2	-30	25.38	25.40	25.41			25.40	25.63	50.00	10.61	529	0.683		0.0559	0.1829	0.239
3 .	-30	25.11	25.13	25.13			25.12	26.29	50.00	10.43	529	2.479		0.0660	0.6706	> 0.739

Comments:

25X 50mm CTOD SPECIMENS
SAW CUT DEFECT
> TERMINATED THE TEST (ABOVE THE CLIP GAUGE RANGE)
2- δ_u value

Date:
Tested By:
Witnessed By:
Project Engineer:

[redacted] CTOD FRACTURE [redacted] TEST LABORATORY [redacted]

TABLE D5

Contract No:

Spec No.	Temp (°C)	a_{25} (mm)	a_{50} (mm)	a_{75} (mm)	a_{min} (mm)	a_{max} (mm)	a_{avg} (mm)	B (mm)	W (mm)	Y	σ_y (MPa)	V_p (mm)	P_{max} (KN)	ELASTIC (mm)	PLASTIC (mm)	δ (mm)
1	-50	26.25	26.06	26.06			26.12	25.91	51.82	10.75	529	0.328	60.50	0.0533	0.0864	0.137
2	-50	25.99	25.95	25.97			25.97	25.91	51.82	10.64	529	0.597	66.55	0.0610	0.1600	0.221
3	-50	25.78	25.56	25.75			25.70	26.11	51.82	10.48	529	0.269	60.94	0.0483	0.0737	0.122
4	-50	26.05	26.01	26.05			26.04	25.96	51.82	10.70	529	0.617	64.99	0.0584	0.1651	0.223
5	-50	26.11	25.83	25.70			25.88	25.96	51.82	10.60	529	0.635	67.17	0.0584	0.1702	0.228
6	-50	25.20	25.11	25.24			25.18	25.71	50.83	10.45	529	0.914	70.28	0.0660	0.2489	0.315
7	-50	25.27	25.21	25.24			25.24	25.71	50.85	10.49	529	1.1252	67.75	0.0635	0.3048	0.368
8	-50	25.13	25.09	25.21			25.14	26.06	50.85	10.43	529	0.3175	61.00	0.0483	0.0864	0.135
9	-50	25.33	25.35	25.41			25.36	25.71	50.83	10.59	529	0.8941	66.05	0.06096	0.2413	0.302
10	-50	25.42	25.37	25.43			25.41	26.29	50.00	10.61	529	0.4140	58.00	0.0457	0.1118	0.16

Comments: 25X50mm CTOD Specimen SAW CUT CRACK
All CTOD values are δ_u values.

Date:
Tested By:
Witnessed By:
Project Engineer:

CTOD FRACTURE TOUGHNESS TEST LABRATORY REPORT

TABLE D4

Cont[illegible]t No:

Spec No.	Temp (°C)	a_{25} (mm)	a_{50} (mm)	a_{75} (mm)	a_{min} (mm)	a_{max} (mm)	a_{avg} (mm)	B (mm)	W (mm)	Y	σ_y (MPa)	V_p (mm)	P_{max} (kN)	ELASTIC (mm)	PLASTIC (mm)	δ (mm)
1	-30	25.04	25.07	25.11			25.07	25.78	50.00	10.39	529	2.5984		0.0686	0.7087	> 0.780
2	-30	25.38	25.40	25.41			25.40	25.63	50.00	10.61	529	0.683		0.0559	0.1829	0.239
3 .	-30	25.11	25.13	25.13			25.12	26.29	50.00	10.43	529	2.479		0.0660	0.6706	> 0.739

Comments:

25X 50mm CTOD SPECIMENS
SAW CUT DEFECT
> TERMINATED THE TEST (ABOVE THE CLIP GAUGE RANGE)
2- δ_u value

Date:
Tested By:
Witnessed By:
Project Engineer:

[redacted] CTOD FRACTURE [redacted] TEST LABORATORY [redacted]

TABLE D5

Cont. [redacted]t No:

Spec No.	Temp (°C)	a_{25} (mm)	a_{50} (mm)	a_{75} (mm)	a_{min} (mm)	a_{max} (mm)	a_{avg} (mm)	B (mm)	W (mm)	Y	σ_y (MPa)	V_p (mm)	P_{max} (KN)	ELASTIC (mm)	PLASTIC (mm)	δ (mm)
1	-50	26.25	26.06	26.06			26.12	25.91	51.82	10.75	529	0.328	60.50	0.0533	0.0864	0.137
2	-50	25.99	25.95	25.97			25.97	25.91	51.82	10.64	529	0.597	66.55	0.0610	0.1600	0.221
3	-50	25.78	25.56	25.75			25.70	26.11	51.82	10.48	529	0.269	60.94	0.0483	0.0737	0.122
4	-50	26.05	26.01	26.05			26.04	25.96	51.82	10.70	529	0.617	64.99	0.0584	0.1651	0.223
5	-50	26.11	25.83	25.70			25.88	25.96	51.82	10.60	529	0.635	67.17	0.0584	0.1702	0.228
6	-50	25.20	25.11	25.24			25.18	25.71	50.83	10.45	529	0.914	70.28	0.0660	0.2489	0.315
7	-50	25.27	25.21	25.24			25.24	25.71	50.85	10.49	529	1.1252	67.75	0.0635	0.3048	0.368
8	-50	25.13	25.09	25.21			25.14	26.06	50.85	10.43	529	0.3175	61.00	0.0483	0.0864	0.135
9	-50	25.33	25.35	25.41			25.36	25.71	50.83	10.59	529	0.8941	66.05	0.06096	0.2413	0.302
10	-50	25.42	25.37	25.43			25.41	26.29	50.00	10.61	529	0.4140	58.00	0.0457	0.1118	0.16

Comments: 25X50mm CTOD Specimen SAW CUT CRACK
All CTOD values are δu values.

Date:
Tested By:
Witnessed By:
Project Engineer:

[redacted] CTOD [redacted] TEST LABORATORY [redacted]

TABLE D6

Cont[redacted]t No:

Spec No.	Temp (°C)	a_{25} (mm)	a_{50} (mm)	a_{75} (mm)	a_{min} (mm)	a_{max} (mm)	a_{avg} (mm)	B (mm)	W (mm)	Y	σ_y (MPa)	V_p (mm)	P_{max} (KN)	ELASTIC (mm)	PLASTIC (mm)	δ (mm)
1	-50	52.58	52.32	52.58			52.58	52.07	105.16	10.61	529	0.490		0.0762	0.1346	0.213
2	-50	52.32	52.32	52.58			52.32	52.32	105.16	10.53	529	0.564		0.0787	0.1575	0.236
3	-50	52.32	52.32	52.58			52.32	52.32	105.16	10.53	529	0.272		0.0635	0.0762	0.140*
4	-50	52.58	52.07	52.32			52.32	51.82	105.16	10.53	529	1.092		0.0864	0.3048	0.391
5	-50	52.32	52.32	52.32			52.32	52.58	105.16	10.53	529	1.712		0.0940	0.4775	0.572

Comments: 50X100mm CTOD SPECIMENS

SAW CUT DEFECT

* - δ_c values
All others are δ_u values

Date:
Tested By:
Witnessed By:
Project Engineer:

TABLE D7. Engineering Stress-Strain Data for the Wide Plate Weld.

Base plate				Weld metal				Cross weld			
1		2		1		2		1		2	
stress MPa	strain %	stress MPa	strain %	stress MPa	strain %	stress MPa	strain %	stress MPa	strain %	stress MPa	strain %
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
197.00	0.09	126.00	0.06	327.00	0.16	118.00	0.06	79.00	0.04	183.00	0.09
358.00	0.17	398.00	0.14	485.00	0.24	240.00	0.12	244.00	0.12	282.00	0.14
453.00	0.23	462.00	0.18	532.00	0.27	382.00	0.19	374.00	0.20	390.00	0.21
413.00	0.24	413.00	0.21	555.00	0.33	465.00	0.23	413.00	0.24	437.00	0.26
398.00	0.26	413.00	0.50	552.00	0.36	556.00	0.28	433.00	0.30	457.00	0.31
400.00	0.27	417.00	0.55	532.00	0.41	567.00	0.33	445.00	0.40	481.00	0.41
400.00	0.35	421.00	0.70	526.00	0.47	567.00	0.37	453.00	0.47	501.00	0.53
396.00	0.38	427.00	0.76	526.00	0.62	552.00	0.48	468.00	0.56	509.00	0.63
396.00	0.46	417.00	2.11	532.00	0.83	542.00	0.57	476.00	0.67	513.00	0.71
402.00	0.52	433.00	2.48	548.00	2.05	533.00	0.77	486.00	0.74	517.00	0.75
402.00	0.72	488.00	4.93	564.00	3.28	541.00	0.91	531.00	2.82	557.00	2.95
418.00	1.45	520.00	7.38	591.00	5.48	567.00	0.91	559.00	5.02	581.00	5.40
409.00	2.06	539.00	9.83	611.00	8.42	587.00	2.26	579.00	7.23	593.00	8.10
433.00	2.68	555.00	13.50	619.00	11.85	611.00	4.71	594.00	10.66	616.00	10.55
472.00	4.64	563.00	17.18	619.00	14.18	626.00	7.40	598.00	12.86	597.00	12.25
500.00	6.60	566.00	20.36	611.00	16.02	634.00	12.06	587.00	15.07	561.00	15.94
531.00	10.27	559.00	24.53	591.00	18.22	630.00	14.51	551.00	17.76	505.00	18.88
547.00	14.44	531.00	29.67	544.00	21.63	595.00	17.69	512.00	19.72	445.00	21.08
555.00	19.34	492.00	32.61	473.00	24.59	542.00	20.63	461.00	21.68	374.00	23.04
555.00	21.79	449.00	34.82	367.00	27.78	485.00	23.23	378.00	24.13	358.00	23.10
551.00	24.97	394.00	37.02			430.00	25.04	358.00	24.62		
543.00	27.91	319.00	38.98			374.00	26.39				
516.00	31.10										
464.00	34.52										
413.00	36.98										
315.00	39.92										

APPENDIX E

TABLE E1. Strain Gauge Readings for Wide Plate Test # 1 (side 1).

Pressure psi	Micro-strains										
	E1	E2	E3	E4	E5	E7	E8	E9	E10	E11	E12
0	-7	-10	0	7	18	18	-5	32	37	28	33
1000	250	203	222	230	200	204	175	336	306	362	392
5000	803	677	692	705	590	662	646	1290	1220	1317	1490
7000	1067	917	926	924	762	875	870	1726	1582	1632	1883
8000	1226	1065	1064	1052	858	1002	1000	1947	1760	1864	2252
9000	1370	1198	1190	1162	940	1106	1118	2170	1918	2200	2720
10000	1500	1320	1290	1260	1010	1202	1220	2370	2080	2690	3272
11000	1630	1450	1435	1360	1110	1300	1340	2660	2352	3510	4040
12000	1710	1530	1515	1440	1190	1370	1420	2910	2554	4030	4672
13000	1800	1570	1630	1560	1300	1460	1540	3500	2762	5410	7275
13300	1830	1520	1632	1530	1290	1415	1530	3830	3004	6720	11245
0	12	-108	-50	-80	1	-258	-254	1718	922	4250	8514

TABLE E1 continued.

Micro-strains

E13	E14	E15	E16
31	29	32	32
370	346	268	241
1704	1503	962	822
2110	1909	1302	1189
2500	2220	1609	1438
3028	2660	1780	1699
3692	3290	1925	1910
4635	4380	2162	2160
5390	5220	2340	2330
8230	7160	2440	2660
9435	9440	2315	2760
6810	7050	375	961

TABLE E2. Strain Gauge Readings for Wide Plate Test #1 (side 2).

Pressure psi	Micro-strain										
	W1	W2	W3	W4	W5	W7	W8	W9	W10	W12	W14
0	6	1	-3	10	27	18	-7	34	37	37	24
1000	179	126	134	119	94	160	166	186	176	170	139
5000	644	493	522	430	293	502	535	514	483	444	386
7000	888	700	728	602	415	685	739	645	597	563	449
8000	1045	839	864	718	495	800	875	713	676	676	505
9000	1190	973	994	829	575	915	1011	783	763	778	580
10000	1330	1100	1110	930	650	1024	1140	860	866	908	690
11000	1480	1240	1260	1060	730	1142	1300	970	1096	1108	890
12000	1600	1360	1380	1160	760	1238	1420	1120	1575	1340	1080
13000	1730	1520	1550	1300	760	1375	1570	1560	2270	3345	2900
13300	1890	1560	1610	1350	710	1415	1620	1910	2652	6465	4750
0	365	271	312	249	-23	344	479	537	1305	5055	3430

TABLE E2 continued.

Micro-strains

W15	W16
17	28
118	109
364	316
498	399
580	446
654	480
723	520
862	580
1095	640
2265	960
2712	1690
1555	710

TABLE E3. Strain Gauge Readings for Wide Plate Test #2.

Pressure psi	Micro-strains										
	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	W1
0	34	20	24	36	47	5	9	3	4	12	23
500	67	64	45	39	25	26	75	126	5	44	181
1000	102	85	75	46	25	56	72	154	33	55	221
2000	216	189	164	110	36	42	154	242	111	129	352
3000	329	293	255	171	49	69	213	327	190	221	469
4000	440	396	341	230	61	83	279	409	265	320	585
5000	552	502	429	293	76	103	305	481	325	433	709
5500	618	561	475	325	83	109	369	554	398	485	773
6000	678	620	525	364	95	119	396	598	460	530	838
6500	739	677	572	397	105	129	436	616	499	569	905
7000	803	735	618	434	117	140	462	655	652	598	962
7500	880	803	670	477	132	150	507	700	522	630	1039
8000	960	871	725	520	149	163	542	756	631	658	1109
8500	1021	928	770	558	162	176	585	822	655	698	1170
9000	1079	982	811	595	177	187	615	833	675	728	1217
9857	1240	1100	905					910	730	785	1355
0		-47	-54	-43	-1	-33	-56	-95	205	-568	-72

TABLE E3 continued.

Micro-strains

W2	W3	W4	W5	W7	W8	W9	W10
21	22	37	53	24	12	12	9
156	163	134	80	62	51	138	147
202	188	182	123	102	94	191	214
319	297	264	170	203	204	391	420
426	391	353	222	284	294	557	592
533	486	435	253	362	390	726	760
647	580	525	302	456	463	905	935
707	630	565	313	499	545	1009	1009
769	682	602	333	545	601	1115	1087
826	730	636	344	583	652	1216	1172
885	775	676	357	621	700	1312	1245
945	824	715	363	658	755	1413	1321
1006	873	754	375	693	811	1506	1424
1055	915	782	381	729	859	1587	1534
1095	944	799	381	750	891	1633	1653
1180	1050				960	1745	1830
-30	-23		-41	-1	-1	-1	

TABLE E4. Strain Gauge Readings for Wide Plate Test #3.

Pressure psi	Micro-strains										
	E1	E2	E3	E5	E6	E8	E9	E10	E15	E16	W1
0	0	0	0	0	0	0	0	0	0	0	0
1000	120	117	119	82	60	47	106	115	116	129	40
5000	665	623	609	483	432	502	708	694	735	762	497
7300	944	877	854	672	609	748	981	962	1053	1043	776
9000	1156	1080	1042	807	739	953	1217	1220	1357	1284	1003
10000	1265	1173	1145	867	798	1071	1373	1388	1549	1433	1127
11000	1388	1389	1285	940	865	1209	1586	1634	1806	1652	1284
12000	1444	1866	1425	999	922	1380	1836	1919	2080	1897	1411
13000	1562	2450	1540	1090	990	1490	2170	2300	2390	2250	1540
13750	1680	2950	1670	1160	960	1760	2670	2770	2960	2740	1670
13950	1700	2990	1670	1110	880	1950	3050	2880	3520	3130	1750
14400		1380	1670	1160	960	1950	3050	2880	3520	3130	
0	-6		90	100	-80	10	10				38

TABLE E4 continued.

Micro-strains

W2	W3	W5	W6	W8	W9	W10	W15	W16
0	0	0	0	0	0	0	0	0
48	45	33	53	126	53	55	63	68
496	493	295	336	657	344	305	355	452
763	784	452	483	993	450	380	438	632
988	1061	543	606	1246	507	423	494	726
1120	1213	674	670	1353	523	444	521	771
1276	1416	778	748	1567	551	446	554	837
1341	1673	876	821	1750	578	543	589	930
1400	1960	1000	890	2140	620	690	640	1120
1450	2530	1090	920	2730	870	1110	910	1380
1500	2760	1140	1030	2970	1260	1550	1300	1550
	2530	1140	1030	2970	1260	1550	1300	1550
-162	1253	131	9	9	-1200		436	9

TABLE E5. Strain Gauge Reading for Wide Plate Test #4.

Pressure psi	Micro-strains										
	E1	E2	E3	E5	E6	E9	E10	E15	E16	W1	W2
0	-7	-6	-5	-18	-11	-19	-13	281	-15	-4	-2
500	66	62	42	-56	-30	14	26	293	-4	165	141
1000	118	107	82	-48	-15	63	81	319	32	214	181
2000	237	213	177	-22	16	164	199	379	114	332	278
3000	355	320	272	0	35	224	306	433	189	453	383
4000	475	424	369	21	54	305	404	488	248	576	491
5000	599	532	468	47	75	405	488	523	313	697	595
5500	679	601	538	65	91	459	526	544	357	768	654
6000	758	666	607	83	106	497	552	560	386	830	704
6500	835	730	665	103	122	536	584	579	413	894	758
7000	905	790	721	126	142	571	614	599	435	948	803
7500	971	845	769	150	161	606	645	621	459	1001	648
8000	1051	912	831	182	187	646	683	645	483	1063	895
8500	1170	1009	927	244	239	714	763	693	530	1141	956
9000	1236	1063	983	255	253	723	795	710	538	1192	994
9500	1304	1117	1040	265	263	727	837	732	537	1238	1030
10000	1368	1168	1095	275	273	732	899	769	538	1280	1061
10500	1423	1212	1147	283	280	738	992	818	537	1315	1088
11000	1498	1278	1224	293	286	769	1174	918	543	1356	1122
11500	1586	1339	1295	300	284	864	1417	1050	564	1400	1141
12000	1649	1380	1343	299	269	1031	1603	1198	647	1418	1141
12500	1659	1413	1377	282	253	1328	1797	1341	895	1411	1135
13000	1715	1448	1401	261	233	1479	1956	1423	1130	1405	1142
13500	1776	1494	1427	236	209	1626	2180	1477	1341	1413	1151
14000	1937	1522	1451	215	187	1776	2410	1524	1493	1433	1153
14500	2050	1545	1477	194	163	1925	2700	1570	1641	1539	1159
15000	2160	1569	1504	174	138	2030	2990	1625	1783	1692	1168
15500	2260	1606	1545	154	118	2130	3490	1710	1929	1859	1191
16200	2430	1670	1610			2270	4200	1830	2130	2080	1230
0	568	58	269	-269						310	-31

TABLE E5 continued.

Micro-strain

W3	W5	W6	W8	W9	W10	W15	W16
-1	-7	-5	0	-7	-4	-4	-4
119	20	32	110	143	170	159	134
152	26	37	130	190	220	203	171
234	56	69	197	308	350	325	282
322	93	112	293	444	499	465	415
412	130	158	399	588	624	605	568
498	163	199	498	701	730	732	708
547	178	213	552	758	794	803	767
589	191	235	599	808	858	865	817
634	207	254	647	867	924	940	882
670	226	275	690	926	1003	1015	954
706	245	295	730	986	1103	1113	1029
748	269	319	775	1060	1239	1256	1117
799	309	354	825	1185	1463	1499	1230
831	310	359	858	1241	1579	1636	1292
859	309	362	892	1310	1731	1814	1377
884	310	370	922	1387	1879	1983	1477
907	308	376	949	1471	2010	2130	1596
934	303	383	986	1611	2160	2230	1784
949	290	377	1023	1773	2330	2330	2030
944	266	349	1052	1951	2260	2300	2270
933	221	324	1066	2130	2330	2270	2530
923	181	300	1056	2250	2400	2260	2680
916	148	272	1050	2370	2490	2280	2880
912	123	247	1044	2470	2600	2330	2890
916	100	213	1043	2570	2780	2420	3000
929	84	186	1054	2650	3050	2530	3090
955	67	162	1083	2740	3600	2740	3200
1020			1140	2840	4100	3050	3370
359	-103	-219	-186	11			

TABLE E6. Strain Gauge Readings for Wide Plate Test #5.

Pressure psi	Micro-strains										
	E1	E2	E3	E6	E8	E9	E10	E15	E16	W1	W2
0	-102	-89	-100	-103	-38	-169	-162	-113	-176	-27	-21
500	-39	-51	-62	-60	95	-13	-47	-27	-80	135	104
1000	55	25	10	-9	201	127	74	89	46	213	167
2000	196	146	123	57	330	311	236	261	218	344	287
3000	346	267	238	116	447	492	402	432	380	479	399
4000	501	393	357	185	553	714	560	587	567	618	520
5000	664	526	478	242	664	868	662	713	742	766	646
6000	804	641	582	287	765	975	741	824	865	897	763
7000	937	748	674	322	863	1062	810	934	969	1029	882
8000	1095	870	780	357	970	1147	900	1077	1069	1162	998
9000	1226	979	875	388	1066	1229	1005	1218	1166	1283	1112
10000	1392	1092	969	424	1163	1332	1168	1485	1278	1408	1228
11000	1494	1175	1031	447	1232	1441	1336	1708	1400	1542	1324
12000	1574	1216	1051	442	1284	1618	1404	1688	1580	1601	1369
13000	1716	1164	1013	385	1300	2070	1559	1625	1999	1793	1339
14000	1781	1154	996	328	1294	2380	1716	1707	2160	1806	1352
14500	1833	1186	1012	290	1310	2600	1920	1894	3290	1820	1401
0	15	-16	-13	-16	6	121	72	-29	-42	15	-3

TABLE E6 continued.

Micro-strains

W3	W5	W6	W8	W9	W10	W15	W16
-21	-106	-59	16	-87	-63	-74	-90
100	-67	-52	57	43	63	13	-14
159	-32	-43	82	116	130	71	38
262	26	-13	160	256	276	193	168
367	90	24	248	404	398	303	298
472	185	76	341	562	554	435	460
581	246	117	442	685	672	568	573
679	280	146	539	785	772	702	663
776	305	173	644	897	898	859	767
867	327	198	746	1029	1057	1075	875
957	345	222	842	1199	1285	1381	1001
1041	363	245	934	1438	1735	1915	1160
1108	379	258	1015	1818	2640	2700	1386
1134	390	237	1075	2290	3230	3220	1794
1130	366	153	1100	3210	3900	3630	2580
1139	346	107	1126	2740	4380	3860	2950
1173	339	92	1160	4310	4980	4200	3270
1	-5	-21	3	16	138	9	78

TABLE E7. Clip Gauge Readings.

	CTOD, mm				
Pressure psi	test #1	test #2	test #3	test #4	test #5
0.00	0.00	0.00	0.00	0.00	0.00
500.00	0.01	0.02		0.01	0.02
1000.00		0.03		0.01	0.04
2000.00		0.05		0.03	0.06
3000.00		0.08		0.06	0.10
4000.00		0.10		0.08	0.12
5000.00	0.06	0.13	0.01	0.13	0.16
5500.00		0.15		0.16	
6000.00		0.18		0.18	0.19
6500.00		0.20		0.21	
7000.00	0.08	0.23	0.02	0.23	0.22
7500.00		0.26			
8000.00	0.09	0.29		0.36	0.27
8500.00		0.33		0.36	
9000.00	0.11	0.37	0.03	0.39	0.31
9500.00		0.43		0.44	
10000.00	0.13			0.51	0.67
10500.00					
11000.00	0.16		0.03	0.64	1.58
11500.00				0.79	
12000.00	0.19			1.02	2.47
12500.00					
13000.00	0.52		0.05	1.28	3.86
13500.00	1.00		0.12	1.61	
14000.00			1.40	2.14	
14500.00			2.69	2.52	
15000.00				3.08	
15500.00				3.43	
16200.00				3.45	

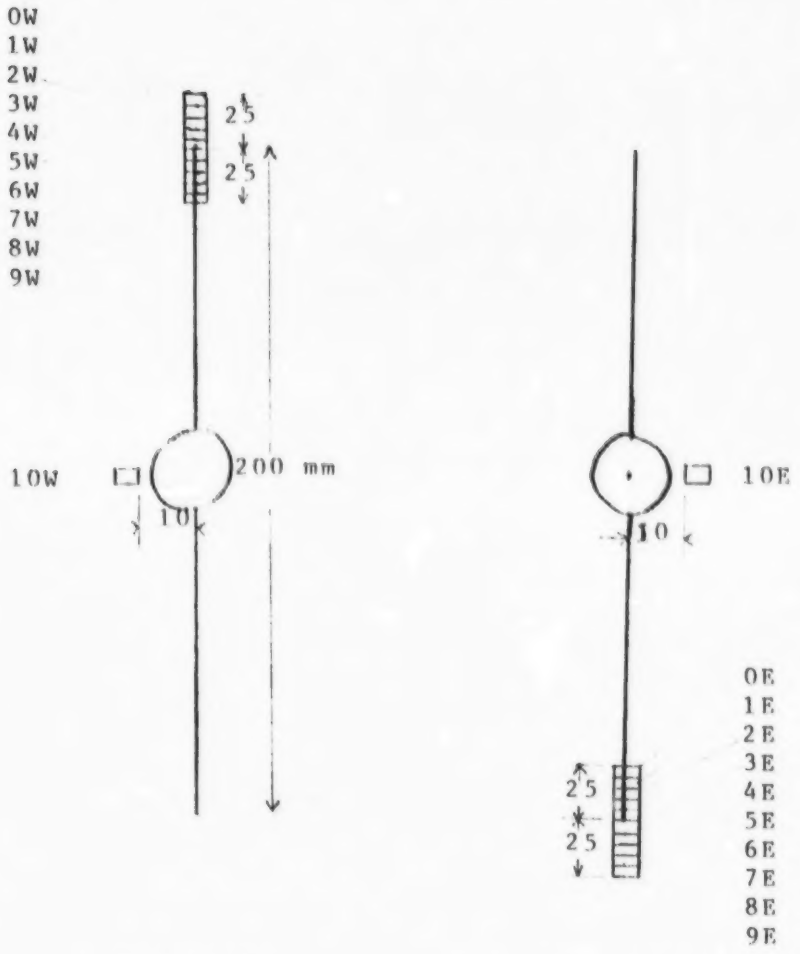


Figure E1. Strain gauge locations for defect cutting.

Cutting of east side gauges:
after drilling of the holes the middle gauges were unhooked, 0W removed for 9E, 7E connected to channel for 10W, 8E connected to channel for 10E, 9E connetced to channel for 0W.

Cutting of west side gauges:
0E gauge removed to connect 0W.

TABLE E8. Micro-strains during cutting of the defect in Wide plate #5.

comments	0W 9E	1W	2W	3W	4W
zero	0.00	0.00	0.00	1.00	0.00
3/8" drill-1" deep	4.00	3.00	4.00	5.00	4.00
3/8" through hole	11.00	10.00	10.00	12.00	12.00
3/4" drill-1/4" deep	8.00	8.00	10.00	11.00	11.00
3/4" drill-1" deep	17.00	17.00	18.00	20.00	19.00
3/4" through hole	26.00	25.00	27.00	29.00	30.00
East side					
start saw cut	-1.00	18.00	18.00	20.00	19.00
15 mm	0.00	17.00	16.00	18.00	18.00
30 mm	14.00	18.00	17.00	20.00	19.00
45 mm	11.00	14.00	13.00	16.00	15.00
60 mm	15.00	17.00	15.00	17.00	15.00
70 mm	15.00	14.00	13.00	14.00	15.00
contact with 0E	16.00	9.00	6.00	7.00	8.00
0E cut	27.00	6.00	4.00	5.00	6.00
1E cut	30.00	7.00	5.00	7.00	7.00
2E cut	22.00	10.00	8.00	11.00	10.00
3E cut	55.00	9.00	6.00	10.00	9.00
86 mm	55.00	12.00	10.00	12.00	12.00
West side					
15 mm	56.00	8.00	3.00	5.00	2.00
30 mm	56.00	4.00	-3.00	-1.00	6.00
45 mm	66.00	-12.00	-22.00	-19.00	-27.00
60 mm	-158.00	-28.00	-39.00	-34.00	-41.00
contact with 9W	-146.00	-33.00	-42.00	-35.00	-137.00
9W cut	71.00	-31.00	-39.00	-30.00	-31.00
8W cut	68.00	-27.00	-33.00	-21.00	-13.00
7W cut	66.00	-14.00	-17.00	0.00	24.00
6W cut	-155.00	-14.00	-8.00	24.00	91.00
5W cut	70.00	32.00	52.00	130.00	355.00
West .012" blade	68.00	40.00	65.00	155.00	457.00
finish .006" blade	0.00	48.00	84.00	212.00	1067.00
East .012" blade	0.00	49.00	86.00	213.00	1066.00
finish .006" blade	0.00	50.00	86.00	214.00	1066.00

TABLE E8 continued.

5W	6W	7W	8W	9W	10W 7E	0E	1E
1.00	1.00	1.00	1.00	-1.00	-5.00	1.00	1.00
4.00	4.00	4.00	3.00	1.00	-66.00	11.00	9.00
12.00	13.00	14.00	15.00	14.00	-300.00	12.00	12.00
13.00	14.00	15.00	16.00	14.00	-335.00	32.00	29.00
20.00	22.00	22.00	23.00	21.00	-425.00	40.00	35.00
32.00	35.00	37.00	41.00	40.00	-1014.00	41.00	37.00
22.00	26.00	30.00	36.00	35.00		50.00	45.00
20.00	24.00	28.00	33.00	36.00		52.00	44.00
21.00	24.00	28.00	33.00	35.00		67.00	56.00
16.00	21.00	24.00	29.00	30.00	12.00	98.00	75.00
19.00	22.00	26.00	32.00	32.00	17.00	231.00	153.00
17.00	19.00	23.00	29.00	31.00	22.00	682.00	310.00
9.00	13.00	16.00	22.00	24.00	30.00	1405.00	395.00
8.00	11.00	14.00	24.00	22.00	42.00	1460.00	666.00
8.00	11.00	14.00	19.00	22.00	49.00		1589.00
12.00	16.00	19.00	24.00	26.00	61.00		
10.00	14.00	17.00	22.00	24.00	101.00		
14.00	18.00	21.00	26.00	29.00	115.00		
2.00	4.00	8.00	14.00	20.00	112.00	1.00	
-6.00	-4.00	-1.00	5.00	6.00	105.00	-3.00	
-31.00	-27.00	-24.00	-16.00	-41.00	91.00	-18.00	
-40.00	-27.00	35.00	7.00	57.00	99.00	-33.00	
-28.00	-2.00	34.00	-37.00	583.00	107.00	-33.00	
-17.00	19.00	85.00	294.00	5000.00	136.00	-30.00	
18.00	86.00	236.00	16000.00		111.00	-31.00	
98.00	294.00	1200.00			129.00	-20.00	
333.00	1500.00				99.00	-19.00	
1600.00					134.00	20.00	
					130.00	28.00	
						27.00	
						30.00	
						29.00	

TABLE E8 continued.

2E	3E	4E	5E	6E	10E 8E
1.00	1.00	0.00	1.00	1.00	-2.00
9.00	8.00	6.00	7.00	7.00	-119.00
9.00	9.00	8.00	8.00	8.00	-163.00
26.00	23.00	19.00	19.00	18.00	-734.00
31.00	28.00	24.00	24.00	23.00	-830.00
33.00	31.00	27.00	26.00	25.00	-878.00
41.00	40.00	29.00	33.00	27.00	32.00
41.00	37.00	33.00	33.00	32.00	2.00
52.00	47.00	41.00	40.00	38.00	9.00
64.00	58.00	49.00	47.00	48.00	12.00
118.00	93.00	74.00	64.00	54.00	22.00
207.00	141.00	97.00	75.00	60.00	19.00
253.00	171.00	115.00	88.00	68.00	25.00
342.00	222.00	147.00	108.00	83.00	33.00
446.00	270.00	171.00	121.00	89.00	37.00
1220.00	449.00	242.00	166.00	113.00	43.00
	1650.00	452.00	265.00	170.00	73.00
		897.00	363.00	212.00	78.00
		906.00	367.00	214.00	78.00
		903.00	365.00	216.00	75.00
		903.00	372.00	220.00	63.00
		915.00	378.00	228.00	70.00
		921.00	380.00	232.00	75.00
		924.00	384.00	232.00	93.00
		912.00	379.00	226.00	87.00
		905.00	368.00	227.00	89.00
		917.00	377.00	231.00	68.00
		928.00	386.00	235.00	91.00
		919.00	381.00	238.00	91.00
		917.00	381.00	237.00	89.00
		1998.00	424.00	248.00	91.00
			580.00	289.00	